Optimising surgical training in primary total hip replacement



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Abstract

Primary total hip replacement (THR) is one of the most performed and successful operations of the 21st Century. However, despite its prevalence and importance, no agreed teaching methods exist for THR overall, or for any of its key steps. Furthermore, little research has been conducted investigating the learning curve of trainees in THR or attempts made to optimise training in this operation using an evidence-based approach. This thesis aims to develop and evaluate novel simulation training methods to improve surgeon performance and patient outcomes in elective primary THR.

A retrospective case series of 348 primary THR demonstrated that operative times and postoperative radiographs cannot be solely used in defining the learning curve and technical skills progression of specialty registrars (StRs) across a 6-month placement. Analysis of National Joint Registry data identified a recent trend for increased early and potentially avoidable revision operations following elective primary THR performed by unsupervised surgical trainees. This highlights the importance of appropriate supervision during trainee performed THR, and the need for continued improvements in training. Expert consensus methodology was used to deconstruct, define, and rank the key steps of a primary THR, and the results used to develop an evidence-based training module for surgical trainees. The impact of this module was then assessed in both simulated laboratory and clinical environments in a group of 34 orthopaedic trainees. A trend for improved knowledge acquisition and templating in THR was observed following simulation training, but no significant differences were observed in simulated skin incision marking, or component orientation tasks. Novel motion analysis techniques have been developed and validated for assessing the intra-operative technical skills performance of surgeons during primary THR. Trainees were significantly slower and performed more movements than consultants in most steps of this operation. However, no significant differences were observed in blood loss, transfusion requirements, patient-reported outcome measures, or post-operative radiographic parameters in relation to surgeon experience. These results support the safety and efficacy of supervised training in THR in relation to patient outcomes. No meaningful clinically important differences were observed in surgeon performance or patient outcome metrics following simulation training in trainee performed THR. However, the small number of trainee (n=7) and patient (n=52) participants in this study were notable limitations.

This research fills an important gap in knowledge regarding how to best train surgeons in primary THR and has identified areas for targeted future improvement in training, which may ultimately benefit patients, trainers, and trainees. Organisations and individuals responsible for delivering surgical training should use the findings of this research to maximise the operative experience of trainees during clinical placements, ensure adequate intra-operative supervision, and consider the use and integration of both simulation training and objective metrics for training and assessing performance, competence, and progression through a training program.

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1. Introduction

1.1 Introduction and rationale for thesis

The importance of a surgeons technical skill in performing operations has been known for generations. (1) The technical skills of a surgeon are determined by several factors, including their cognitive capability, experience, judgment, decision-making, and manual dexterity. (2) All surgeons should have an innate physical and mental ability to learn and master technical skills. Therefore, with sufficient time, training (teaching and assessment), practise and experience an individual's surgical skills are likely to improve. The process of training orthopaedic surgeons to competently perform operations requires the accumulation of scientific knowledge, technical skills, operative experience, professional judgement, alongside sufficient supervision until competence is achieved. This process is time-consuming, costly, and susceptible to variations in the healthcare systems and environment in which surgeons are now trained. Surgical education is a life-long process, which starts with a period of generic surgical training followed by specialty-specific and increasingly sub-specialty-specific training, which is then followed by high-quality continuing medical education. (3) The traditional apprentice-style model of surgical education described by William Halstead involves a graduated and repetitive exposure of trainees to managing patients and performing operations under the supervision of a skilled and experienced surgeon. (4) Although the same principles apply in contemporary surgical training programmes, restrictions in both working times, and the volume and breadth of in-training surgical experience has required an increasingly focused approach to maximise the opportunities for trainees to achieve operative competence prior to completion of their training. (5, 6) The indicative minimum number of surgical cases required by the Joint Committee for Surgical Training (JCST) for completion of training may not be sufficient to acquire competency. (7) This situation has been compounded by the recent global COVID-19 pandemic, which has significant negative implications for the future of orthopaedic training. (8) Simulation training is now a recognised educational modality which supplements traditional apprentice-style training. Simulation has been described as a technique not a technology, to replace or amplify real experiences with

guided experiences that evoke or replicate substantial aspects of the real world in a fully interactive manner. (9) There are clear advantages to using simulation in surgical training, which allows trainees to acquire, practice, and develop essential procedural skills in the safety of a non-clinical environment before refining them intra-operatively under the supervision of an expert.

Primary THR is one of the most performed and successful orthopaedic operation of the 21st Century. (10, 11, 12) The projected future demand for primary THR is expected to rise significantly within developed countries such as the UK, USA, and Australia. (13, 14, 15) Training orthopaedic surgeons is therefore crucial to provide a highly skilled workforce capable of meeting this rising demand. Despite its prevalence and importance, there are no agreed teaching methods for THR overall, or for any of its key steps. Furthermore, it is unknown if surgeons even agree or disagree about the key steps and how best to teach them. Novel approaches to surgical training must be cost-effective and demonstrate a clear positive impact on either the rate of attainment of knowledge, surgical skills acquisition, real-world performance metrics and proficiency, or patient outcomes to justify their widespread adoption in training programmes. Regulatory bodies within the United Kingdom that are responsible for setting standards in surgical education and training currently recommend the use of standardised Procedure-Based Assessments (PBA) tools and surgical experience, as reflected by first surgeon operative numbers in indicative specialty-specific procedures, for determining the proficiency of surgical trainees technical procedural skills. (16, 17) However, there is increasing demand for improvements in these methods of assessment to objectively assess and define surgical competence to ensure patient safety. (3) Any assessment tool should be feasible, objective, valid, and reliable. (18) Without these key attributes training programmes cannot ensure satisfactory surgical skills acquisition and competence, tackle deficiencies in training, and implement remedial measures. (19) Little research has been conducted investigating the learning curve of trainees in THR and identifying the key differences in surgeon performance and patient outcome metrics for novice in comparison to experienced surgeons. (20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30) This research aims to fill an important gap in knowledge in surgeon performance metrics and patient outcomes following THR which may help to identify areas for targeted future improvement in training which may ultimately benefit patients, trainers, and trainees.

1.1.1 Aim

The aim of this thesis is to develop and evaluate novel surgical simulation training methods to improve surgeon performance and patient outcomes in elective primary total hip replacement.

1.1.2 Objectives

This aim is addressed through the following objectives:

1. Perform a retrospective analysis of surgical trainee performance and learning curves in primary elective THR during clinical arthroplasty training placements.

2. Define the incidence of serious adverse patient outcomes (revision or mortality) following elective primary THR using National Joint Registry (NJR) data.

3. Define the key steps of a primary THR which are either critical to patient outcomes or difficult to teach clinically.

4. Develop a novel, simulation-based training module in primary THR for orthopaedic surgical trainees.

5. Develop and validate a novel motion analysis system for analysing and objectively quantifying intra-operative surgeon motion.

6. Assess the impact of additional simulation-based training on the knowledge and technical skills performance of orthopaedic trainees in both a simulated and intra-operative clinical environment.

7. Compare and contrast the technical skills performance and patient outcome metrics of surgical trainees against expert consultant hip surgeons in primary elective THR to identify key differences and areas for future improvements in training.

Literature Review

1.2 Assessment of technical skills in the domain of surgery

Assessment of technical procedural skills is fundamental for trainees to progress through a surgical specialty training programme and achieve certification of competence in a particular procedure. These assessments are considered a form of quality assurance for the future. (31) Surgical skills may be categorised into generic and procedure specific. Generic surgical skills are those that may be applied across a broad range of specialities and procedures. Generic surgical skills include tissue handling, maintaining sterility of the surgical environment, economy of hand movement, knowledge and appropriate use of instruments, and the utilisation of surgical assistance. Procedure specific surgical skills are those that are required in addition to generic skills to complete a particular procedure. Surgical procedures are often complex tasks, which are defined as having many steps to successfully complete the procedure. The individual steps may themselves be simple or complicated depending upon the level of technical difficulty required to complete them. Furthermore, the individual steps of a procedure often need to be performed in a particular sequence to achieve the desired outcome. Blencowe *et al* have described methodology to deconstruct and standardise complex surgical operations into component steps for the purposes of reporting outcomes in scientific studies. (32) This methodology may be applied in surgical training to enhance the recording of trainees actual surgical experience in the individual steps of complex operations within their logbooks. (33) Group consensus methodologies such as the Delphi technique are also a recognized tool to formulate an expert group opinion on key steps of a particular surgical procedure.

An optimal assessment tool for measuring surgical skills performance should be task-specific, standardized, objective, validated for its purpose, reliable, and feasible for it to be widely accepted and utilized. (18, 34) Without these key attributes training programmes cannot ensure proficiency in skill acquisition, tackle deficiencies in training, and implement remedial measures. (19) The five principles of validity with respect to the assessment of surgical technical skills are: construct, content, concurrent, face, and predictive validity. Construct validity describes how well an

assessment can differentiate the performance between two surgeons with different technical abilities. Content validity describes how well an assessment tool measures what it purports to measure (i.e., surgical technical skills). Concurrent validity describes how well an assessment tool performs in comparison to the other available validated tools. Face validity describes how representative of reality the assessment tool is. Predictive validity describes how well the assessment tool can predict future performance. The reliability of an assessment tool is a measure of its reproducibility when administered on different occasions and by different observers. Inter-rater reliability (also referred to as inter-rater agreement or kappa statistic) has been defined as the amount of agreement between two or more raters who follow the same procedure. (35) A highly reliable surgical assessment tool infers that different raters show no significant variations in their scoring when judging the performance of a surgical trainee.

The importance of developing and implementing relevant, validated, reliable and objective proficiency models was highlighted in a cross-specialty review article on the role of simulation-based surgical education. (36) Measurement tools used to assess technical surgical skills may be categorised into structured human grading systems, or dexterity analysis systems. (2) The authors of a review paper on implementing simulation-based orthopaedic surgical skills training have commented that "meticulously defined procedure-specific tasks should be assessed using standard measurement protocols that combine more than one objective technique, such as OSATS, motion analysis, and direct objective metrics" (37). This highlights the importance of defining the task or skill to be assessed in advance of determining the best method/s of assessment. Benchmarks in quantitative performance metrics that are set by experts in their field have been suggested for use in proficiency-based progression models of training. (37, 38) The authors suggest that attainment of the pre-defined benchmark performance metrics by a surgical trainee during a simulated task or procedure would provide quantitative evidence of proficiency.

1.2.1 Structured human grading systems

Structured human grading systems aim to provide a structured extension of the traditional human observational approach to evaluation using standardised ratings systems or checklists. Examples of subjective human grading systems in surgical assessment include: Objective Structured Assessment of Technical Skills (OSATS) (39, 40), Global Rating Systems (GRS) (41), Procedural-based assessments (PBA), Objective Structured Clinical Examinations (OSCE) (19, 42), checklists, and Error Score Card Analysis (43).

1.2.1.1 Objective Structured Assessment of Technical Skills (OSATS)

OSATS were first developed and validated at the University of Toronto in 1996. (44) They consist of seven generic components of operative skill marked on a 5-point Likert scale, with the middle and the extreme points anchored by explicit descriptors to help in the criterion referenced assessment of performance. OSATS have been reported as the gold standard for skills performance assessment in open surgery and simulation. (40, 45) However, studies have proven that OSATS scores do not always correlate with the quality of surgical outcome. (46, 47) OSATS have been validated for assessing operative skills in surgical trainees, and are more reliable than task-specific checklists. (39)

1.2.1.2 Global rating scales (GRS)

GRS provide a general measure of performance in each step of a surgical procedure. GRS consist of a 7-item table of technical performance, with each item graded on a 5-point Likert scale. Task and procedure-specific GRS have been developed and validated to assess surgical performance. Examples include the American Academy of Orthopaedic Surgery (AAOS) GRS (48), Basic Arthroscopic Knee Skill Scoring System (BAKSSS) GRS (49, 50), and the Arthroscopic Surgical Skill Evaluation Tool (ASSET) (51, 52, 53).

1.2.1.3 Procedural-based assessments (PBA)

PBAs are a validated form of a global rating system, which are used within most UK surgical training programmes for assessing trainees' procedural skills in the operating theatre (16, 54) The primary purpose of PBAs is to provide structured feedback in a particular area of clinical practice. PBAs are by definition procedure-specific, however they also contain six generic areas of surgical competency assessment, namely: consent, preoperative planning, preoperative preparation, exposure and closure, intra-operative technique and post-operative management. (55)

1.2.2 Dexterity analysis systems

Dexterity analysis systems provide quantitative metrics of relevant surgeon motion whilst performing tasks, including: the number, smoothness, speed, and magnitude of hand movements and the path length travelled. (56, 57) A variety of such systems have been used to assess and report upon surgeon performance metrics in both simulated and real-world tasks. (49, 56, 57, 58, 59, 60) A review of the evidence for various methods used in objectively assessing surgical skills was undertaken by Darzi *et al*. (19) This review highlighted the lack of validity and reliability in the more traditional modalities of assessment, including: examinations; surgical logbooks; non-criteria based direct observation of procedures; time taken to perform a procedure; and the morbidity/mortality of patients. The authors advocated using validated objective methods of technical skills assessments during training such as checklists, global rating systems, and dexterity analysis systems. To be an effective and viable modality of data capture, these monitoring systems must be small, comfortable to wear, user friendly, not interfere with the surgical environment (for example sterility in theatre) or the equipment required for undertaking the procedure (for example attachment of sensors to instruments), or the movement of the operator performing the procedure being under investigation (for example wired motion detectors). Motion tracking can be based upon electromagnetic, mechanical, or optical systems. (61) Wired electromagnetic motion tracking systems, such as the Patriot® (Polhemus®, Colchester, VT) allow precise tracking of sensors placed on the hands or elbows of surgeons within an electromagnetic field generated by an emitter. The feasibility, validity,

and reliability of the Patriot® motion tracking system in objectively assessing surgical skills has been proven in studies simulating arthroscopic and laparoscopic procedures. (56, 62, 63) However, the bulky configuration of these wired systems limits their use to assessing simulated tasks or procedures within a laboratory environment. To overcome these barriers, the development and implementation of wireless sensor technology has become popularised as an alternative method for assessing surgeon motion. Inertial sensors collect accelerometery and gyroscopic data at high sampling frequency and transmit the data wirelessly to computers for analysis using Bluetooth® technology. Analysis of the raw motion data may be performed using either open- or closed-access software to produce output metrics representative of surgeon motion such as speed, direction, smoothness, and total path length of hand movements. Although the validity of wireless sensor technology in assessing surgical performance has been proven in both simulated and real-world arthroscopic procedures (57, 60), there remains a lack of uniformity and standards when reporting the results of studies which use motion analysis metrics. The relative merits of both wired and wireless systems, and the performance metrics generated are explored in further detail in chapter 6.

1.3 Simulation in surgical training

The aviation and nuclear power industries, along with the military, have all embraced the success of simulation-based training programmes to enhance learning and safety. These fields all share intrinsic hazard and complexity but are considered Highly Reliable Organisations (HRO), which demonstrate a very low failure rate considering their inherent risks. Surgical training shares a similar high-risk profile to these industries, which has stimulated the interest, development and utilisation of simulation-based training. (64) The use of simulation in medical and surgical education has been described as "any activity which aims to imitate a system or environment with the aim of assessing, informing and modifying skills and behavior". (65) There are clear advantages to the use of simulation-based training as an adjunct to supplement traditional clinically based training and experience. (65, 66, 67) Simulation training may be used to optimise physician education and performance, enhance patient safety, and improve both the quality and potentially the efficiency of delivering healthcare. Evidence of the use of simulation models for the purposes of medical education dates back millennia. (68) Historical medical simulators used simple materials such as clay, leather, wax, ivory, and metal to produce anatomical models for use in teaching and training. The earliest recorded use of simulators for surgical skills training are contained within the Sushruta Samhita, an ancient Indian textbook of medicine and surgery thought to date back to the 6th Century BC. (69) Rapid advances in both materials and healthcare technology over the last century have facilitated an exponential growth in the breadth, complexity, and realism of simulation models used in contemporary medical and surgical education. Contemporary orthopaedic surgical simulators may be categorised as dry lab, wet lab, digital platforms, hybrid simulators, and mock scenarios. Each of these modalities has a unique profile of advantages and disadvantages, which must be balanced when determining which modality to use for a particular purpose. Ultimately the choice of modality and specific model used should be guided by the procedure or task in question. Considerable variations exist in the cost, fidelity, feasibility, and level of evidence supporting the effectiveness of surgical simulators. The concept of fidelity in relation to simulation techniques refers to how realistic the simulation model appears to the learner (physical fidelity) and does the task replicate what is

expected in real-world performance (functional fidelity). In general, the fidelity of a simulator should match the complexity of the procedure or task to be replicated. (37) A review article reported that 93.5% of 433 commercially available medical simulators have not been validated for their use. (70) However, a systematic review on orthopaedic simulation-based training tools found that 62% of studies (n=47/76) reported on the validity of the simulator used, with knee arthroscopy simulators found to be the most studied. (71) Further systematic reviews have also highlighted that both construct, and concurrent validation has been demonstrated across several arthroscopy simulators. (58, 72)

1.3.1 Orthopaedic surgical simulators

Dry lab simulation models utilise synthetic materials that are manufactured to recreate normal or pathologic anatomical specimens for use in surgical training. These models are relatively easily accessible, reproducible, and modern synthetic bones can mimic the mechanical properties of real bone. For these reasons synthetic models are commonly used for both elective and trauma orthopaedic surgical simulation training. (50) Wet lab simulation models use human cadaveric human or animal (commonly porcine or bovine) tissue specimens. Human cadaveric specimens possess the highest levels of physical and functional fidelity, and for this reason have been considered the gold standard for surgical simulation training. (73) However, cadaveric specimens are expensive, carry a risk of transmissible diseases, and within the UK, a special license for their use is required from the Home Office. The use of cadaveric specimens in surgical simulation-based training is limited to well-funded and licensed institutions with appropriate access to specialized facilities. The condition of cadaveric specimens may also vary dependent upon the preparation method used (fresh frozen or embalmed), and the quality of tissues degrade with repeated use. Furthermore, the consistency in anatomy may vary between specimens, and specific pathological conditions of interest may not be present. These factors reduce the reproducibility in user experience.

Digital simulation training platforms such as virtual reality (VR) and augmented reality (AR) rely upon an entirely computer-generated interface to simulate an immersive experience for the user. The principal difference between these emerging technologies is that real-world surroundings are completely replaced by a digital model in VR, whereas AR digitally alters the user's perception of their real-world environment. Multiple sensory modalities may be used to augment the experience of both VR and AR technologies to create hybrid simulators. (74) These may incorporate visual, auditory, haptic, and somatosensory simulation that combine sensory feedback to users in order to recreate a more realistic experience. (75) The digital models and surgical scenarios generated on these platforms may be adapted for specific training purposes and are highly reproducible by allowing all users to undertake the same training. These digital simulation technologies are reliant upon expensive hardware, software, system maintenance costs, and user familiarity. However, they often occupy a relatively small space and require no special licences for use. This increases their feasibility for use in contemporary surgical training programmes, but their cost-effectiveness requires additional consideration and justification. (76) Although the use of VR simulation training models is now well established in arthroscopic surgery, there is emerging evidence for its application in open orthopaedic procedures. (66, 77, 78, 79) Currently AR simulation training models remain in their infancy, but research studies have highlighted the great potential for future development and validation of this technology for training in open orthopaedic procedures such as total hip replacement. (74) Further studies are required to determine the cost-effectiveness, transfer validity, and impact on patient outcomes of VR simulation training in orthopaedic surgery, and to explore its use and impact outside the arthroscopic field in other commonly performed open operations such as hip and knee replacement. A recent review article has highlighted that the COVID-19 pandemic may act as a catalyst for further development and implementation of AR and immersive simulation within orthopaedic surgery. (8)

Mock scenario simulation attempts to recreate real-life scenarios of patient care situations in a controlled but realistic environment, such as an operating theatre, outpatient clinic consultation, or emergency department. Medical simulation mannequins, human actors or actual patients may be

used in addition to other healthcare staff and invigilators/assessors. This type of simulation requires sufficient staffing with administrative personnel, educators, and clinical experts to ensure authenticity as well as to provide the necessary feedback to learners. Mock scenarios are therefore a costly but high-fidelity form of simulation. Mock scenarios are useful to recreate and assess the performance in non-technical skills, including situational awareness, decision-making, task-management, communication and teamwork and leadership. (71, 80, 81) Scaled down versions of mock scenarios are commonly used in medical and surgical teaching and training, such as in the Advanced Trauma Life Support (ATLS) course, and in the assessment of clinical skills performance during post-graduate examinations, such as in Objective Structured Clinical Examinations (OSCE).

1.3.2 Implementation and use of simulation in orthopaedic surgical training

Focussed and task-specific simulation training provides the opportunity for trainees to learn, practice, and develop defined psychomotor surgical skills in a controlled environment outside the confines, time-constraints, pressure, and risk of a clinical setting. Simulation models may be developed and adapted to recreate specific aspects or the entirety of a particular procedure. Simulation training may be delivered at any time and importantly does not jeopardise patient safety or the efficiency and productivity in delivering clinical care within a healthcare environment. Simulation training may also be useful in the assessment of complex technical surgical skills required for managing emergent critical conditions that are rarely encountered in clinical practice. Examples of such conditions specific to orthopaedic surgery may include paediatric supracondylar humeral fractures, or lower limb compartment syndrome requiring fasciotomies. The role, type, and timing of delivery of simulation training for surgical skills development and assessment in trainee selection, specialty certification, and re-certification is yet to be defined. (38) Surgical simulators may also be used in the assessment of surgical skills acquisition and attainment of competence in a particular task or procedure. (82) This may be particularly important given the shift in emphasis of contemporary post-graduate surgical training towards more competency-based models. (83, 84, 85, 86) However, consideration must be given to which tasks or procedures are best suited for simulation-based

training, how much simulation training is required, and at what point during training is this most effective. (38) There is some evidence that simulation training may be useful in identifying trainees who are underperforming and potentially in need of remediation. (66, 87) Although simulation training may be undertaken as self-directed learning or under the supervision of expert surgical trainers, it is important to recognise the role of quality supervision and structure, as there is little point in practising skills that are performed poorly. Some of the major limitations in determining the true impact of simulation training on surgical performance include the heterogeneity and lack of standardised well-validated objective outcome metrics that are used to assess performance across different studies. (71, 88) This was highlighted in a review article on simulation-based orthopaedic surgical skills training, which recommended that all simulation-based courses include clear objectives and outcome measures (with metrics). (37) The variance in reported outcome metrics, breadth of surgical skills and procedures (diagnostic and/or therapeutic tasks performed in a variety of anatomic joint simulators), and relatively small samples of participants within each study, sometimes without a comparator group, all decrease the ability to draw firm conclusions regarding the impact of simulation training on technical surgical skills performance. Agreement and consistency in the reporting of both standardised validated objective technical skills performance metrics and other assessment tools is therefore needed within future studies that attempt to determine the impact of surgical simulation training. (58, 89) Despite these limitations, contemporary surgical training programmes have embraced and incorporated simulation as a recognised educational modality. Within the United Kingdom, the JCST has agreed to the pan-specialty integration of simulation training across each specialty curriculum. (65) An online survey of orthopaedic program directors and residents in the USA reported that 80% of program directors and 86% of residents agreed that the use of surgical skills simulators should become a required component of training, and that 82% and 76% respectively were interested in a standardised surgical skills curriculum. (90) Although the majority of cross-specialty post-graduate surgical training programmes in developed countries recognise the importance and value of simulation training, many barriers remain to the full integration of this training modality into contemporary surgical training. (36) A review article of the availability and role of simulation in surgical education and training within the UK reported the

results of a 2012 national survey of surgical trainees. (65) A total of 1130 surgical trainees completed this survey, of which only 41.2% reported having access to skills simulation training facilities, with provision and availability varying widely between regions, trainee level and surgical specialty. For example, only 26.6% of the 233 orthopaedic trainees who completed this questionnaire reported access to a simulation skills facility. In 2013 the American Board of Orthopaedic Surgery (ABOS) recommended introducing a mandatory formalised basic surgical and motor skills training course for all first year orthopaedic residents. (36) A review article focusing on the challenges of implementing simulation-based skills training in orthopaedic surgery highlights the important principal that both "simulators and curricula must be rigorously assessed and validated so that training can be proven to be valuable and performance can be reliably assessed". (37) More specifically, the content, construct, concurrent, face, predictive, and transfer validity of each individual simulation skills training module must all be assessed and deemed appropriate for purpose prior to any recommendations for their integration into training programmes and curricula. Validating the transferability of surgical skills from the 'bench top to the bedside' is perhaps the single most important test in determining the true impact of simulation training. However, only a small proportion of studies investigating the role of simulation training on surgical performance have reported on transfer validity. (48, 56, 57)

1.3.3 Simulation training in THR

The vast majority of research within the field of surgical simulation training has focussed on minimally invasive operations, such as laparoscopic or arthroscopic procedures. (45) A limited number of studies have evaluated the use and impact of simulation training on surgeon performance metrics, and no published study has linked any changes in performance metrics to patient outcomes following open orthopaedic procedures, such as hip or knee replacement. A gap in knowledge and understanding of the role of simulation training in commonly performed open orthopaedic procedures therefore exists and is an emerging area of research interest. A systematic review on educational methods in hip surgery published by De Boey *et al* in 2020 identified only 9 articles on

training in either hip arthroscopy or arthroplasty. (91) Several studies have described designing and/or using VR based simulation-training models in THR. (66, 75, 78, 79) A prospective randomised-controlled trial by Logishetty *et al* aimed to evaluate the effectiveness of an AR training program and simulator on achieving a pre-determined acetabular cup orientation in a group of 24 Medical Students. (92) Half of the participants were randomised to receive a 4-week course of AR-based training, with the comparator group receiving teaching from expert hip surgeons. Technical performance evaluations were performed at baseline and following completion of either the AR or expert training programs. At final evaluation, no significant differences were found between groups in their achievement of planned acetabular cup orientations, suggesting that this AR simulator was equally effective in comparison to expert face-to-face training of novices in performing this technical skill. Another prospective observational study by Logishetty *et al* aimed to determine the impact of a VR simulation training program on resident performance in both VR and dry bone simulated THR models performed through a direct anterior approach (DAA). (66) The primary visuospatial performance metrics assessed on the dry bone model were the femoral osteotomy angle and height relative to the lesser trochanter, and acetabular component orientation. Additional performance metrics obtained from the VR assessments included the task duration, hand and head movements, number of errors encountered, and prompts required by users. A total of 32 residents and 4 expert hip surgeons were recruited in this study, with residents undertaking a median of 4.8 hours of VR simulation-training in this complex surgical procedure. At baseline, the resident's performance was significantly poorer than experts in all domains, confirming the construct validity of this simulator model. However, most residents achieved an expert level of performance in acetabular cup orientation and femoral osteotomy height in a median training time of 4 hours. Hooper *et al* published a single-blinded randomised-controlled trial investigating the impact of VR simulation training on the performance of a small group of 14 junior orthopaedic residents during a cadaveric primary THR. (79) All participants within this study undertook a baseline and final multiple-choice questionnaire written assessment and performed a primary THR on a cadaver. The performance metrics scored by expert hip surgeons during the simulated primary THR included a surgical checklist and global rating scale. No objective metrics such as the time taken for task completion, or component positioning

assessments were included for analysis. Following baseline assessments, half of the participants were randomised to receive additional VR simulation training, which included performing two THR on the VR simulator. At the final assessment no significant differences were found between groups in test scores. However, the VR trained group demonstrated significant improvements in their overall cadaveric performance scores in comparison to the control group. A similar prospective randomised-controlled trial by Logishetty *et al* aimed to determine if residents trained using a VR simulation program out-performed control subjects during a cadaveric THR performed through a direct anterior surgical approach (DAA). (78) A total of 24 orthopaedic residents participated, who were randomised into two equal groups. The intervention group received a 6-week VR-based simulation-training program, lasting approximately 1 hour per week, with the control group receiving standardised preparatory literature. All participants were then asked to perform a primary THR on a cadaver, which scored by two blinded experts on a task-specific checklist and procedure-based assessment (PBA). The times taken to complete the procedure and acetabular component inclination angle were also assessed. The authors reported that VR-trained residents outperformed control participants in median PBA scores, completed 33% more key steps on the checklist, were more accurate in achieving the desired acetabular component orientation, and were 9 minutes (18%) faster to task completion. These studies suggest that VR-based simulation training is effective for delivering technical acquisition in residents, which are translated into improved performance metrics in both laboratory based and cadaveric models. A lack of high-quality evidence exists supporting the transferability of technical orthopaedic skills acquired following simulation-based training on real-world intra-operative performance, especially in open operations such as hip and knee replacement. (72, 93, 94) This may be due in part to the financial cost, time, and human resources required to design and conduct transfer validation studies. (71) This research aims to determine whether additional simulation training improves either the intra-operative surgeon performance metrics of orthopaedic trainees during primary THR (transfer validation), or patient outcomes following primary THR.

1.4 Total Hip Replacement

1.4.1 The hip joint and total hip replacement

The hip joint, or acetabulo-femoral joint, is a complex multi-axial di-arthrodial synovial ball-and-socket joint. The acetabulum forms the socket, which itself is formed at the confluence of the bones of the pelvis (ilium, pubis, and ischium); and the femoral head forms the ball. The native hip joint is inherently stable. Its stability is derived from a combination of the congruency of its bony structure, and both static (acetabular labrum, ligaments, and capsule) and dynamic stabilisers (hip musculature). The primary function of the hip joint is to support and transfer the weight of the body onto the leg/s in both static (standing) and dynamic (walking or running) postures. Osteoarthritis (OA) of the hip joint is a common pathological condition resulting in progressive degeneration of articular cartilage, increased friction and joint reaction forces causing a varying degree of pain, stiffness, disability, and possible deformity. (95, 96) Although the aetiology of hip OA is multifactorial, primary hip osteoarthritis is the most common. Secondary hip osteoarthritis results in the same joint degeneration, but is caused by other inciting factors, such as trauma, infection, hip dysplasia, inflammatory arthropathy, osteonecrosis, malignancy, or metabolic conditions.

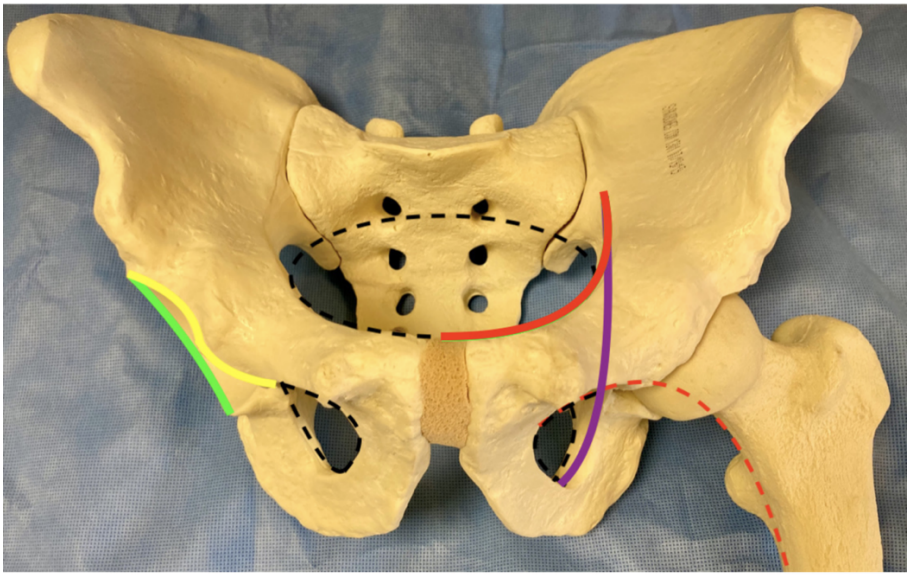
Figure 1-1: Bony anatomy of the pelvis.

A. Synthetic bone model of the pelvis and proximal femur demonstrating the hip joint with labelled anatomical structures.

B. Plain antero-posterior radiograph of the pelvis and proximal femora

C. Plain antero-posterior radiograph of the pelvis and proximal femora with labelled anatomical structures

A

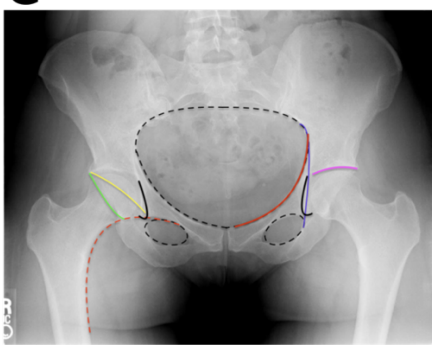


Line	Anatomical Structure	Line	Anatomical Structure
Dashed black	Pelvic ring (superior) and obturator rings (inferior)	Dashed Red	Shenton's line
Solid Red	Iliopectineal line (Anterior column)	Solid Pink	Acetabular roof / Sourcil
Solid Purple	Ilioischial line / Köhlers line (Posterior column)	Solid Green	Posterior acetabular wall
Solid Black	Acetabular teardrops (End-on projection of a bony ridge running along the floor of the acetabular fossa)	Solid Yellow	Anterior acetabular wall

B



C



THR is the most common and cost-effective surgical procedure for end-stage OA of the hip joint, which has justifiably been described as “the operation of the century”. (10, 12, 95, 97) THR may be performed for many reasons, but the overwhelming indication is primary OA of the hip joint. (12) The 18th Annual report of the National Joint Registry (NJR) highlights that OA was the indication for THR in 91.3% of the 1,142,684 cases recorded. (98) The NJR is the single largest joint registry in the World, with all surgeons and hospitals required to complete a data collection form for every joint replacement performed, including primary THR. The principle aims of THR are to reduce pain, correct any underlying deformity, improve range of movement, and restore normal hip biomechanics. Restoration of normal hip biomechanics during THR is known to improve patient function & satisfaction; reduce the incidence of complications; and significantly increase the longevity of the implants. (99, 100, 101, 102, 103, 104) Studies have suggested that the demand for THR is set to almost double within the next two decades, which carries a significant healthcare economic burden. (12, 13, 96, 105, 106) Despite the constant evolution of surgical technology, techniques, implant design, and material science, the principal design features of modern THR originated from the pioneering work of Sir John Charnley’s low friction arthroplasty in the 1960’s. (12, 107, 108) THR involves removing both the femoral head and residual acetabular cartilage and subchondral bone and replacing them with prosthetic components which are fixed into the femoral shaft and pelvis, respectively. In general, fixation of the femoral stem and acetabular cup components is achieved either with or without bone cement. Cemented components sit within a mantle of polymethyl methacrylate (PMMA) which forms a stable interface between the bone and the component. Uncemented/cementless components are partially or totally coated with a thin layer of hydroxyapatite (HA) and are press fitted into the bone to achieve primary stability, with subsequent osteointegration of the bone into or onto the HA coating resulting in secondary ‘biological’ fixation. The bearing surface or articulation of a THR is formed between the liner of the acetabular cup and the head which sits on top of the femoral stem. The materials commonly used in contemporary acetabular liners are highly cross-linked polyethylene or ceramic, with femoral heads composed of metal (cobalt/chromium) or ceramic. High early failure rates have been reported in metal-on-metal articulations in THR, which has reduced their use in contemporary practice. (109, 110)

Figure 1-2: Prosthetic components and constructs used in THR.



Uncemented THR
- uncemented femoral stem (metaphyseal HA coating)
- uncemented acetabular cup
- ceramic femoral head shown



Hybrid THR
- cemented collarless polished tapered femoral stem (cement not shown)
- uncemented acetabular cup
- ceramic femoral head shown



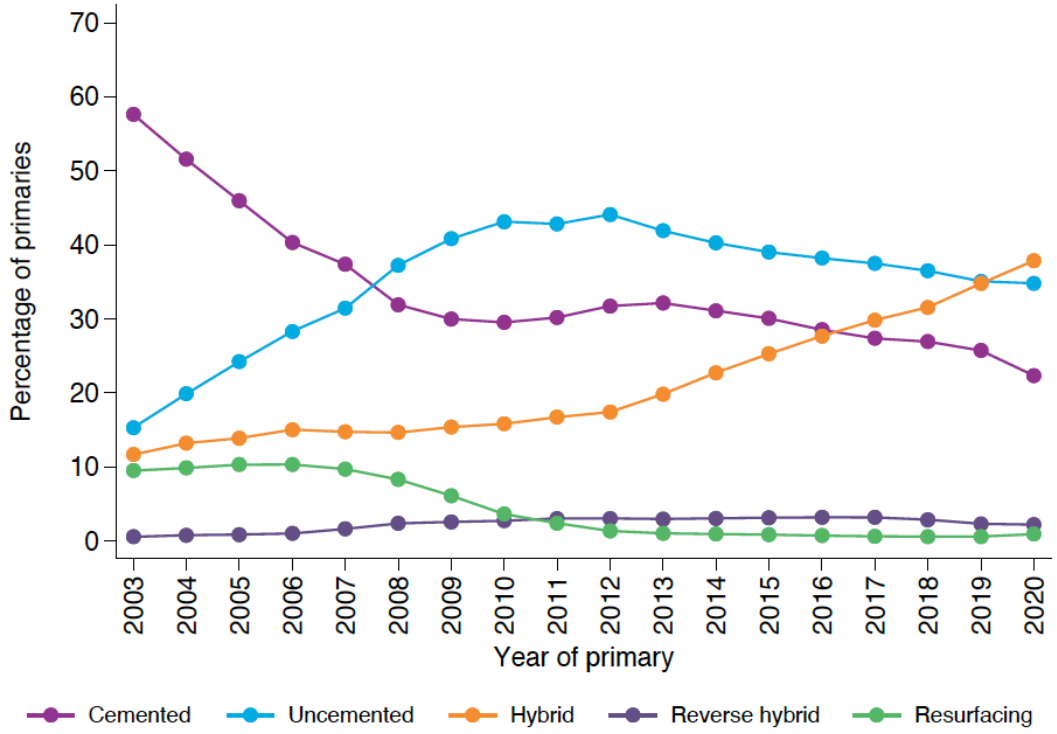
Uncemented Acetabular Cups
- ceramic liner (left)
- vitamin E impregnated highly cross-linked polyethylene liner (middle)
- standard highly cross-linked polyethylene liner (right)



Cemented Acetabular Cup
- PMMA dimples, peripheral flange and metallic radiographic marker shown

Detailed discussions regarding the relative indications and use of specific implant fixation, bearing surface, and head size is beyond the scope of this research, however it is important to note the temporal changes in since the inception of the NJR in 2002. The 18th Annual NJR report highlights that hybrid implant fixation (cemented femoral stem and uncemented acetabular cup) is currently the most used combination of component fixation (37.9%), metal heads on polyethylene liners are the most commonly used materials for the bearing (48.4%), and 32mm femoral heads represent the highest percentage used in primary THR. (98)

Figure 1-3: Temporal changes in THR implant fixation. (98)



1.4.2 Complications and modes of failure in THR

THR is a major operation which involves relatively small but significant risks. The potential complications of THR may be categorised as early, intermediate, or late. Early complications occur either intra-operatively, or in the immediate few days following surgery. Such complications include intra-operative fracture or penetration of either the femur or pelvis, component mal-positioning (causing leg length discrepancy, poor function, or instability) excessive blood loss requiring transfusion, or neurovascular injuries (commonly of the sciatic nerve, or femoral nerve/blood vessels). Intermediate complications occur days to weeks following THR, and include wound problems, venous thromboembolism (VTE), prosthetic joint infection (PJI), peri-prosthetic fracture (PPF) and instability. Late complications occur months to years following THR and include instability; wear related osteolysis and aseptic loosening, PJI, PPF, or component failure. Failure of a THR is usually defined as an endpoint when a revision procedure is undertaken.

1.4.2.1 Instability/dislocation

Instability and dislocation are amongst the most common indications for revision THR procedures. (12) The stability of a THR is compromised by iatrogenic disruption of both the static and dynamic stabilisers of the hip during the surgical approach, and a smaller prosthetic head/cup articulation. Secure closure of the hip capsule and surrounding soft tissue envelope is critical to reduce the incidence of early post-operative instability and dislocation. A systematic review reported that patients undergoing THR using a posterior approach without soft tissue repair had an 8.2 times greater relative risk of dislocation than with soft tissue repair. (111) Component mal positioning is a known risk factor for impingement, instability, dislocation, and increased wear rates in THR (12, 112, 113, 114, 115, 116). Lewinek *et al* reported that the dislocation rate for THR with acetabular cup orientation with radiographic anteversion (RA) of 15 +/- 10 degrees and radiographic inclination (RI) of 40 +/- 10 degrees was 1.5%, while outside this "safe" range the dislocation rate was 6.1%. (114) The ‘Lewinek safe zone’ of cup positioning was born out of the results of this study. Subsequent studies have highlighted scientific flaws in the methodology and conclusions used in

this study. (115, 117) A recent CT-based study investigating the role of acetabular component positioning on hip stability reported that 32% of unstable hips were in the Lewinek safe zone, and that the safe zone for acetabular cup anteversion is narrower than it is for inclination. (118) The authors of this study proposed a new safe zone of 43º+/-12º inclination with 31º +/- 8º of tilt-adjusted acetabular cup anteversion. Reducing the femoral offset during THR reduces the abductor lever arm, which may cause a limp, patient dissatisfaction, increased joint reaction forces, and increased risk of instability and dislocation caused by a combination of inadequate abductor tension and impingement of the femoral neck on the acetabular rim on the extreme ROM. (101, 116, 119, 120, 121, 122)

1.4.2.2 Prosthetic Joint Infection (PJI)

PJI is a rare but major complication of THR, which may occur at any stage following the primary procedure and often requires revision surgery. (97) Several modifiable and non-modifiable risk factors have been identified for developing PJI after THR. (12, 123, 124) The patient factors associated with a higher risk of PJI include: males, high body mass index (BMI), diabetes mellitus, dementia, previous native hip joint septic arthritis, and hip fractures. (123, 124) The surgical factors which have been associated with a lower risk of PJI include a posterior surgical approach, use of ceramic heads, and reduced operative time. (123, 124, 125)

1.4.2.3 Peri-prosthetic fracture (PPF)

PPF is another rare but devastating complication of THR, which again may occur at any post-operative stage and often requires revision surgery. (126) PPF may occur on the femoral or acetabular sides of the THR, but fractures of the femur are far more common. These injuries are associated with high patient morbidity and mortality. (127) Risk factors associated with PPF include trauma, increasing age, female gender, osteoporosis, osteolysis and aseptic loosening, and certain femoral stem implants. (12, 126, 127, 128)

1.4.2.4 Aseptic loosening

Aseptic loosening is a common late cause of failure in THR, which is frequently caused by particulate wear debris induced osteoclast driven osteolysis at the bone to implant, cement to implant, or cement to bone interfaces. (12, 97) Component mal positioning is a known risk factor for increased wear rates causing osteolysis and aseptic loosening in THR. (112, 113)

1.4.2.5 Leg length discrepancy (LLD)

LLD following THR is a common cause of patient dissatisfaction, poorer functional outcomes, limping, back pain, instability, and is a common reason for surgeon litigation. (129, 130, 131, 132, 133, 134, 135) LLD following THR may also be an indication for revision surgery if patients suffer significant pain or functional impairment as a direct result of it. (133) Considerable effort must therefore be made to achieve balanced and equal leg lengths for the patient. Surgeons are more likely to inadvertently increase a patient's leg length during a THR than shorten it. (103, 136) Post-operative LLD is most commonly due to mal positioning of the femoral component, rather than the acetabular component. (102, 129) Perceived LLD following THR is common, with one study finding that 30% of patients reported a LLD between 5-8 years following a primary unilateral THR. (129) Although these patients reported a significantly lower Oxford Hip Score (OHS) than subjects who did not experience a functional LLD, a subsequent radiographic analysis revealed that only 36% of these patients had an anatomical LLD. Minor LLD, usually defined as <10mm, are generally well tolerated by patients, and any discomfort settles over the first few post-operative months. (131, 133, 136, 137) A study using calibrated blocks on healthy subjects (n=30) reported that no participants reported discomfort with a 5mm LLD, whereas almost 97% noticed an artificially induced LLD of >10mm. (138)

1.5 Contemporary orthopaedic surgical training requirements in THR

Surgical training standards and certification guidelines within the UK graduate medical education system are formed through a complex interaction between several advisory, regulatory, and professional bodies. Advisory bodies, such as the JCST in the UK, are responsible for evaluating and recommending standards relating to all aspects of training across the ten surgical Specialty Advisory Committees (SACs). As the parent organisation for SACs, the JCST works closely with professional bodies such as the Royal College of Surgeons (RCS), regulatory bodies such as the General Medical Council (GMC), and statutory education bodies such as Health Education England (HEE) to ensure that all surgical trainees meet the minimum requirements outlined within the curricula and guidelines for practising as a specialist in their surgical field. Specialty specific surgical associations, such as the British Orthopaedic Association (BOA), also act as advocates for specialty training and education standards through their collaboration with the JCST, SAC, RCS, and other healthcare policy advisors in the NHS and wider Government. However, the JCST and SACs are ultimately responsible for recommending doctors to be added to the GMC specialist register once all conditions of their training have been satisfactorily completed. This recommendation is issued in the form a certificate of completion of training (CCT). Recognised medical education and training institutions across the UK assess surgical trainees' knowledge, clinical judgement and decision-making abilities using standardised summative written post-graduate examinations in combination with objective-structured clinical examinations. These assessments form the basis of the Joint Committee on Intercollegiate Examinations (JCIE) Fellowship examinations in Trauma & Orthopaedic Surgery.

Contemporary trauma and orthopaedic specialty surgical training programmes within the UK are a minimum of 6 years in duration, which is divided into 6-month clinical placements. The JCST and SAC curriculum stipulates that trainees must undertake clinical placements in all eight trauma & orthopaedic sub-specialties during the indicative 6-year training programme. This should leave a period of 2 years at the end of training for trainees to undertake special interest placements in their

chosen sub-specialty. Trainees can expect to perform a median average of 28 THR as first surgeon during a 6-month clinical placement in adult reconstructive/arthroplasty surgery. (23) This figure varies depending upon several recognised surgeon and institutional factors, including: trainee seniority and ability; surgical case mix and training opportunities presented by trainers; and balancing other departmental commitments and duties such as on-calls and clinics. For these reasons trainees often require at least 3 clinical placements in arthroplasty to achieve the requisite 80 major joint arthroplasty number for CCT. This figure represents a quarter of the total training programme, and is a significant burden for trainees, trainers, and programme directors. The fractious nature of training also means that these placements may not be sequential, and retention of sub-specialty specific operative skills may be lost between placements. Therefore, any interventions to accelerate or improve the learning curve training in arthroplasty would be advantageous in contemporary trauma and orthopaedic surgical training.

Experienced Clinical Educational Supervisors (CES) and other registered surgical trainers are responsible for assessing the practical technical skills orthopaedic surgical trainees using formative procedural-based assessment (PBA) tools. Assessors of PBAs are required to provide a global summary of a trainee's performance in a procedure rated on a scale of 1 to 4. Level 1 represents an inability to perform the procedure under supervision, and level 4 represents competence in performing the procedure without supervision and the ability to deal with any potential complications that arose. Surgical trainees are required to obtain level 4 PBAs in all indicative procedures listed in their specialty-specific certification guidelines published by the JCST. Current guidelines from the JCST for certification in trauma and orthopaedic surgery stipulate that trainees require three level 4 PBAs in major joint arthroplasty (hip, knee, shoulder, ankle joints) from at least two or more trainers, alongside a total of 80 cases as first surgeon to meet CCT requirements. (17)

2. Defining the performance and learning curve of orthopaedic trainees in primary elective total hip replacement

This study has been published in the Annals of the Royal College of Surgeons of England in July 2021 (23)

2.1 Introduction

Assessing a trainees technical skills performance is challenging, although many different methods have been proposed, including: PBA; operative times (139); time action analysis (140); and the learning curve cumulative sums method (L-CUSUM). (141) Senior trainees generally show shorter times to perform the same procedure compared with junior trainees and importantly, if appropriate supervision is in place, there is no difference in short-term complication or revision rates. (22) Analysis of postoperative radiographs is a well-established method of surgical performance assessment following THR but is not well described as an indirect measure of a surgeon's learning curve. (142) An ideal tool to measure learning curves should be validated, easily accessible and provide minimal extra resource. This study evaluates readily accessible information, including postoperative radiographs and operative times, to determine if these parameters can define the learning curve of trainee orthopaedic surgeons in elective primary THR.

2.2 Aims

The aims of this study are to:

1. Investigate the performance of a cohort of orthopaedic surgical trainees in elective primary THR using operative times and routine postoperative radiographic parameters.
2. Assess if these performance metrics change in trainees over a 6-month period whilst on clinical placements in adult arthroplasty.
3. Investigate the effect of supervision and assistant grade on postoperative radiographic parameters and operative times.

2.3 Methods

Study design and ethical approval

This is a retrospective cohort study. Evidence level III.

The online Healthcare Research Authority (HRA) decision tool was used to determine that formal ethical approval was not required for conducting this study. Approval was obtained from the orthopaedic department prior to retrieving any study data using electronic patient record systems.

Participants and study setting

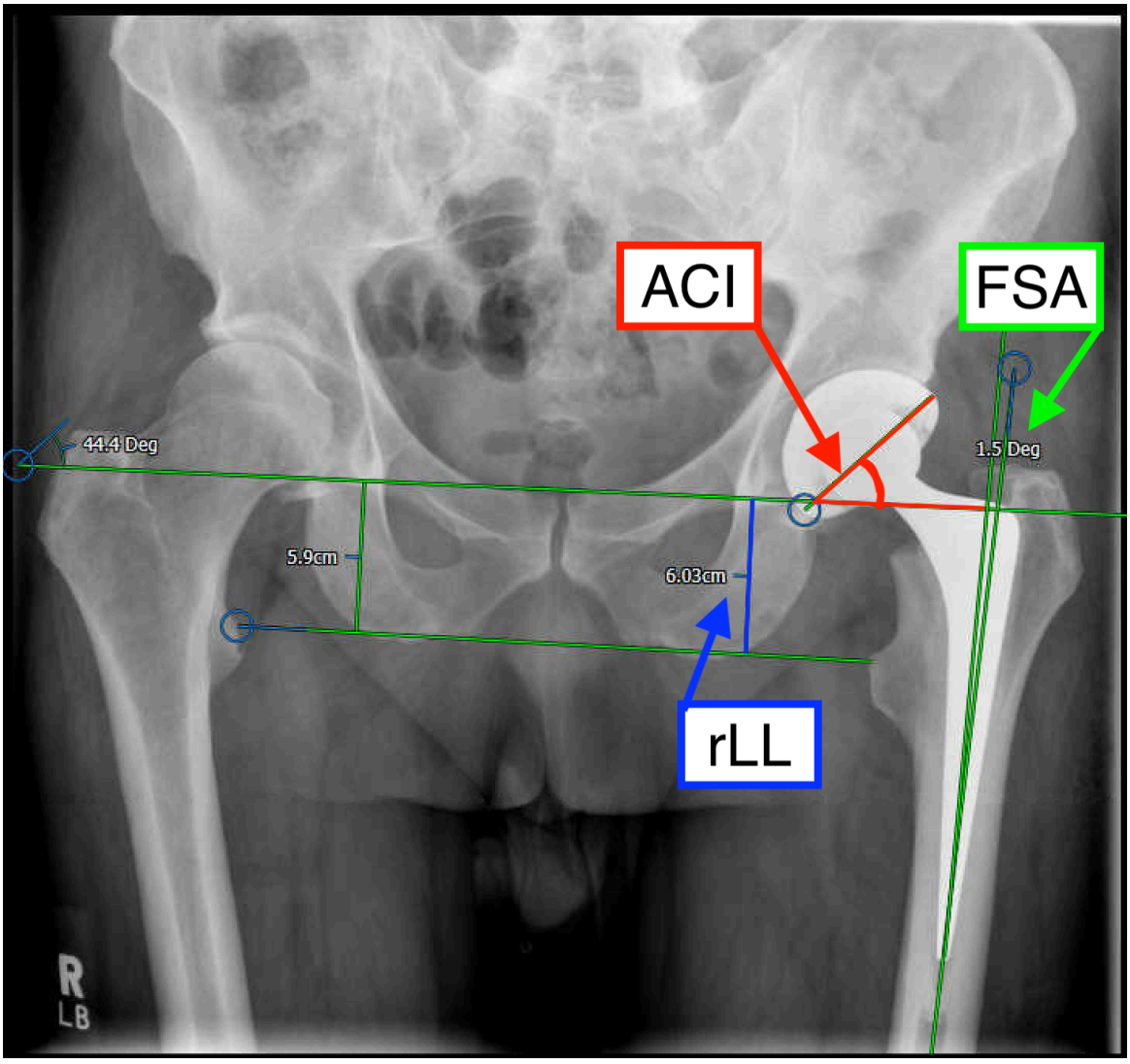
No patient or surgeon participants were recruited into this study. Electronic surgical logbook (e-logbook) data were requested and volunteered from orthopaedic specialty registrar trainees (StRs) who had completed clinical placements in the adult arthroplasty department of the Nuffield Orthopaedic Centre (NOC) during their orthopaedic higher surgical training programme. The NOC is a specialist tertiary level NHS university teaching hospital, and forms part of the Oxford University Hospitals NHS Foundation Trust.

Outcome measures and statistical analysis

Primary THR (pTHR) operations performed by StRs as first-surgeon were identified and cross-referenced with the hospitals digital electronic patient records (EPR; Powerchart, Cerner Corp., Kansas City, MO, USA) and picture archiving and communications system (PACS; Insignia Medical Systems, Basingstoke, UK) to perform the radiographic analysis and obtain theatre operative timings. The operation notes on EPR were used to gather information regarding the level of supervision and grade of first assistant for each pTHR. Radiographic evaluation and scoring were performed by four orthopaedic surgeons using postoperative plain anterior–posterior (AP) pelvic radiographs. All assessors were blinded to the StR who performed the operation. The following radiological parameters were assessed: acetabular cup inclination (ACI); radiological leg length discrepancy (rLLD); femoral stem alignment (FSA) in the coronal plane; and the Barrack score for quality of femoral cementation. The inter-teardrop (IT) line was used as the pelvic reference for

assessing ACI. The angle subtended between the long axis of the acetabular cup and the IT line was used to determine ACI. The IT line was also used as the pelvic reference for assessing rLLD. A second line connecting the most prominent medial border of both lesser trochanters was drawn, and perpendicular lines were drawn connecting this line to the IT line above to determine rLL of both legs. The rLLD was determined by subtracting the rLL from the non-operative side (the right leg in figure 2-1) from the operative side (the left leg in figure 2-1). The FSA was determined by the angle subtended between a line down the anatomical axis of the femur and a second line starting from the tip of the femoral stem travelling up the midpoint of the stem.

Figure 2-1: Post-operative AP pelvic radiographic demonstrating the methods used to calculate ACI, rLL, FSA.



Inter-rater reliability (IRR) for scoring each radiological parameter was determined using a two-way random effect, average measure of agreement with a 95% confidence interval (CI) on a random sample of ten postoperative radiographs which were independently rated by the same four researchers. The value of kappa ranges from 1 (perfect agreement), to -1 (perfect disagreement). (143) The criteria outlined by Koo and Li were used in this study, who recommend that kappa values <0.5 indicate poor reliability, 0.5 to 0.75 indicate fair reliability, 0.75 to 0.9 indicate good reliability, and >0.9 indicates excellent reliability. (144, 145, 146) Radiographic evaluation was performed only for cases in which complete and adequate postoperative pelvic radiographs were available.

Individual StR total number of pTHR cases were subdivided into two equal groups, representing their performance for the first and second halves of their 6-month placement. Summary group, subgroup and individual-level data is presented using descriptive statistics. The Shapiro-Wilk test was used to determine the distribution of operative time data at the group level. This indicated that the operative time data were not normally distributed ($p < 8.843e-07$), and non-parametric statistical tests were used for statistical analysis between groups. Mann–Whitney U tests were used to analyse continuous individual and group-level data. The Kruskal–Wallis rank sum test was used to analyse continuous data for more than two groups. Pearson's chi-squared test was used to analyse categorical data. The significance threshold was set at 0.05 for all statistical analysis. Data analysis and visualisation was performed by the lead researcher (DJH) using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA).

2.4 Results

Surgical logbook data was provided by twelve StRs working under the supervision of five consultants between February 2010 to September 2019. Operative timings were not available for the StRs who completed their placements prior to the implementation of TMS (StR #1 and #2). A total of 348 pTHR operations performed by StRs as first-surgeon were identified. The median number of supervised pTHRs performed by StRs during their 6-month placement was 28 (range 15-51). The majority of pTHRs were hybrid implant combinations (n=324, 93.1%) with cemented femoral stems and uncemented acetabular cups. Operative time was available for 292 cases, and radiographic evaluation was performed in: 331 cases for acetabular cup inclination; 319 cases for leg length discrepancy; 348 cases for femoral stem alignment; and 322 cases for femoral cementation.

Inter-rater reliability for radiological scoring

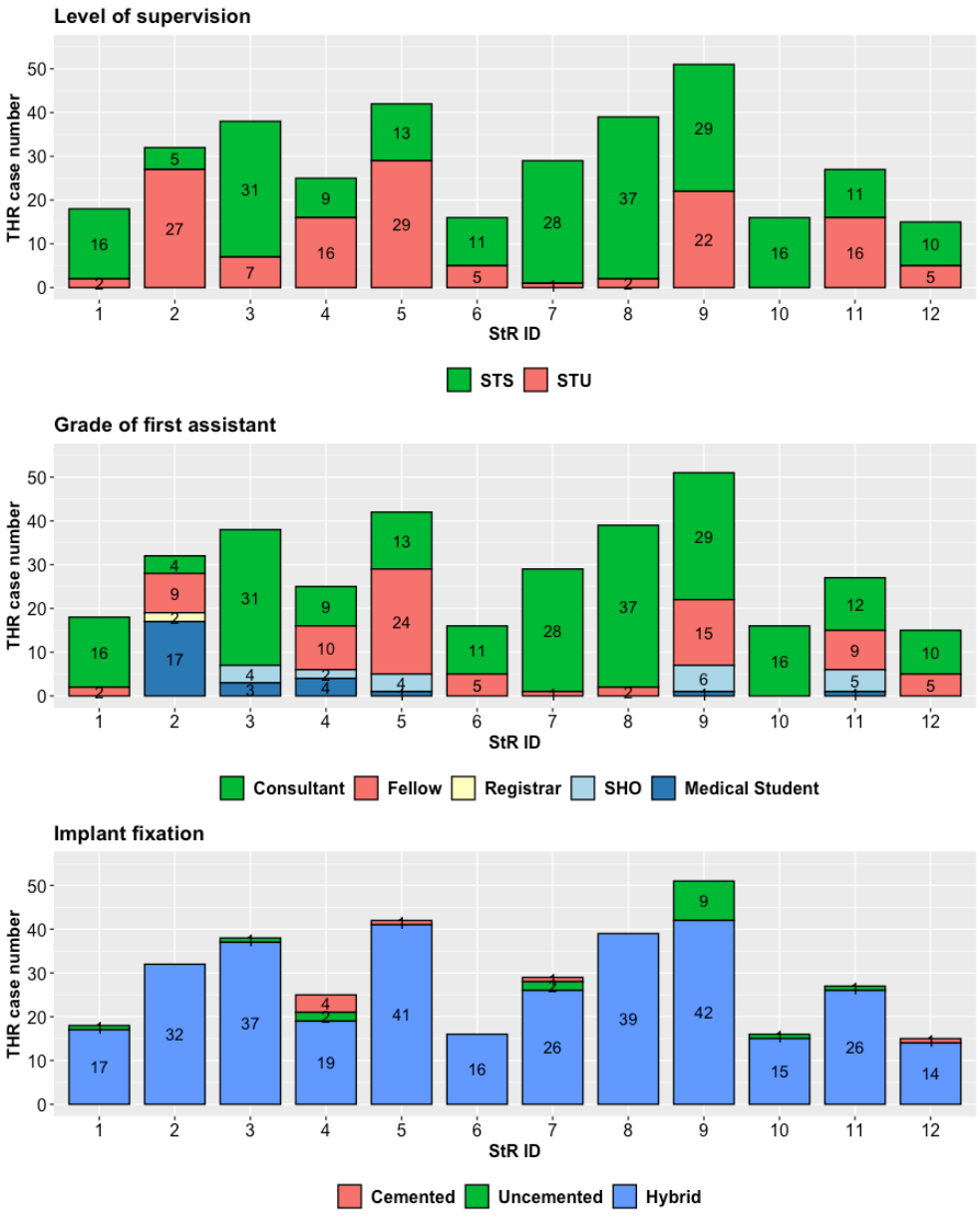
The IRR for ACI scoring was 0.99 (95% CI 0.98–0.99), and 0.97 (95% CI 0.91–0.99) for rLLD indicating excellent reliability. The IRR for FSA scoring was 0.68 (95% CI 0.09–0.9), and 0.54 (95% CI −0.268–0.868) for the Barrack score in quality of femoral cementation indicating fair reliability.

2.4.1 Supervision & Surgical Assistant

In total 216 of the StR first-surgeon pTHR (62.1%) were supervised with the trainer scrubbed (STS), and 132 (37.9%) were supervised with the trainer un-scrubbed (STU) but present in the theatre complex (Figure 2-2). A significant difference in the level of supervision was identified within the cohort of StRs ($p < 0.01$), ranging from 15.6% to 94.9% of pTHR STS. Overall, there was no significant difference across the StR group between the level of supervision in the first or second halves of their placements, however a single StR (#3), performed significantly more pTHR with STU in the second half of their placement ($p=0.01$). Most surgical assistants were consultants (n=216, 62.1%), with fellows (n=82, 23.5%), StRs (n=21, 6%), Senior House Officers (n=27, 7.8%), and Medical Students (n=2, 0.6%) representing the remaining assistants. A significant difference was observed in the grades of surgical assistants within the StR group ($p < 0.01$). Overall, there was no

significant difference across the StR group in the grade of surgical assistants between the first or second halves of their placements, however two StRs (#3 and #9) demonstrated significant differences in the grade of surgical assistants in the first and second halves of their placements (p =0.01 and 0.02 respectively), with a trend for less experienced assistants in the second half. Summary information of supervision, grade of first assistants and implant fixation over the whole study period are displayed in figure 2-2.

Figure 2-2: Stacked bar plots demonstrating the level of supervision, grade of first surgical assistant, and implant fixation used in primary THR performed by StRs.



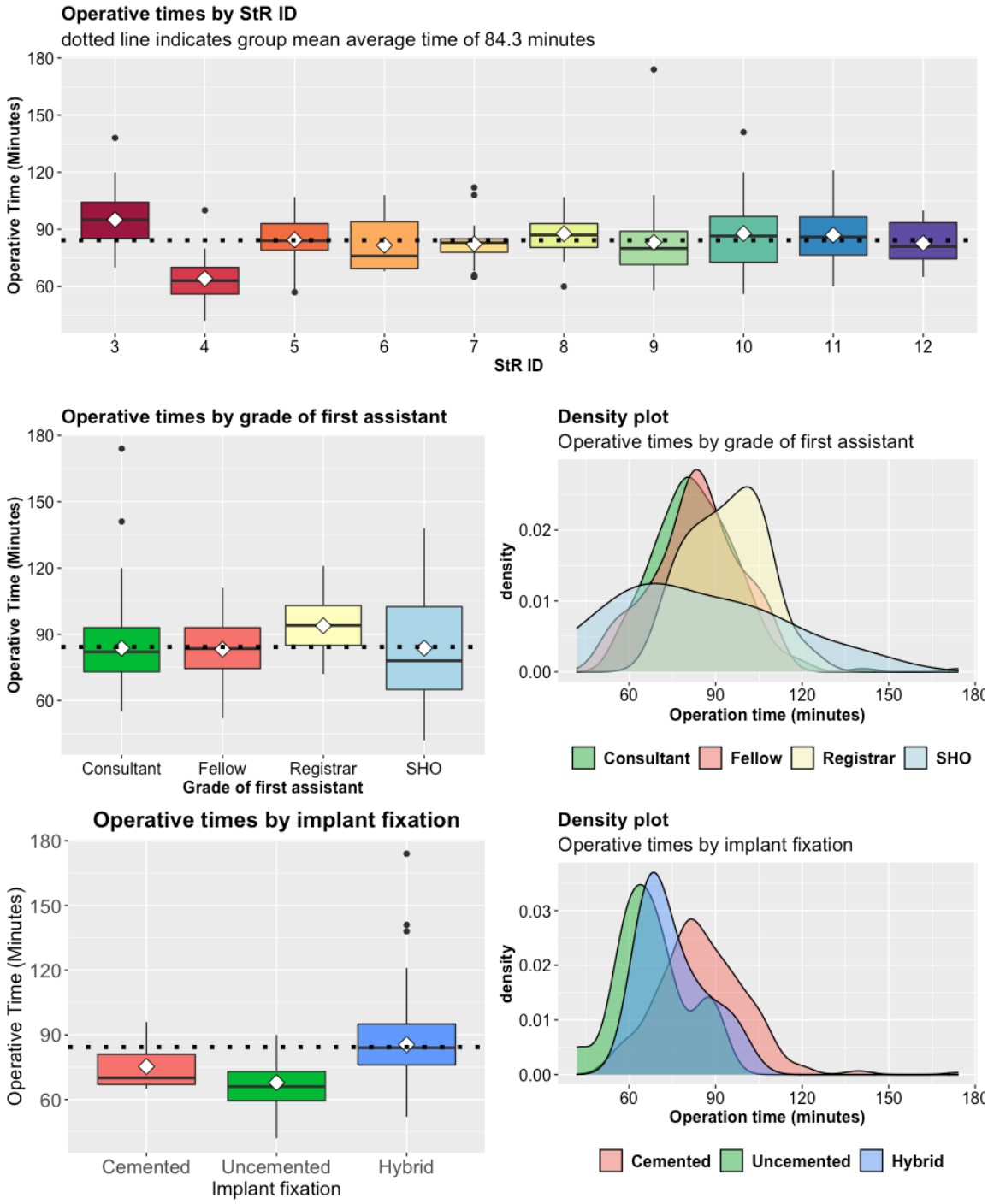
2.4.2 Operative times

The mean operative time for a pTHR was 84.3 minutes (range 42-174, SD 16 minutes). No significant difference in operative times were found at a group or individual level between the use of different implant fixation combinations (hybrid/uncemented/cemented), and therefore the remainder of the analysis was performed using total pTHR data instead of implant-based sub-analysis. A significant difference was observed between StRs individual summary placement operative times ($p < 0.01$). The fastest mean time was 64.1 minutes (range 42-100, SD 11.5 minutes) for StR #4, and the slowest mean time was 95 minutes (range 70-138, SD 14.0 minutes) for StR #3. As a group, there was no significant difference in operative times between the first and second halves of the placements. Two StRs (#7 and #9) had significantly faster operative times in the second half of their placements, and a single StR (#11) had significantly slower operative times in the second half of their placement. No significant differences in operative times were identified across the StR group according to the level of supervision, although two StRs (#9 and #12) were noted to have significantly slower operative times when STU ($p = 0.02$ and $p < 0.01$, respectively). A significant difference in operative times was observed between the StRs according to the grade of surgical assistant ($p = 0.018$), with slower operative timings noted with StRs as assistants, in comparison to consultants, fellows, or SHOs. Two StRs (#9 and #12) were also noted to have significantly slower operative times when assisted by fellows or SHOs in comparison to consultants ($p<0.01$). Figure 2-3 summarises operative times for both individual trainees and according to assistant grade and implant fixation.

Figure 2-3: Boxplots and density plots demonstrating the distribution of operating times for primary THR for each StR.

Graphs subset according to grade of first surgical assistant and implant fixation.

The dotted line on each boxplot represents the mean group time, and the diamond indicates mean time per StR.



2.4.3 Radiological parameters

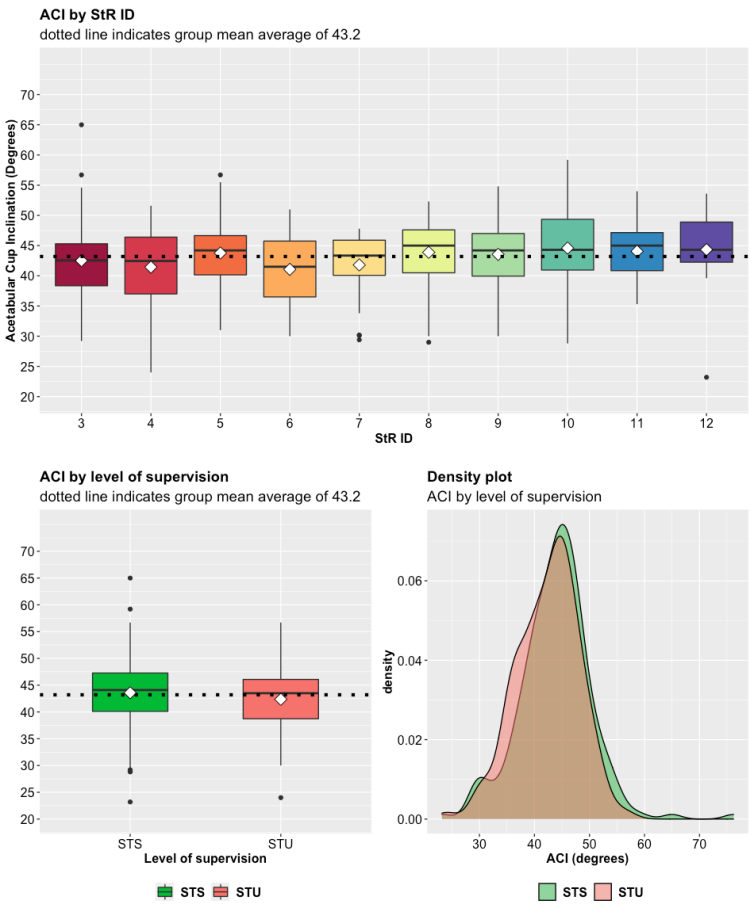
2.4.3.1 Acetabular cup inclination (ACI)

The mean ACI angle for all cases was 43.2°. No significant differences in ACI were observed between placement halves at an individual or group level (group mean 1st half of placement ACI = 42.9°, 2nd half of placement ACI = 43.7°, p=0.28). As a group, there was a significant difference in ACI angles according to the level of supervision, with STS demonstrating higher mean ACI (43.8°) compared with STU (42.4°) (1.2°, 95% CI 0.000026-2.5, p=0.04). No significant overall group difference was noted according to surgical assistant grade, except for a single StR (#11).

Figure 2-4: Boxplots and density plots demonstrating the distribution of ACI for each StR.

Graphs subset according to level of supervision.

The dotted line on each boxplot represents the mean group time, and the diamond indicates mean ACI per StR.

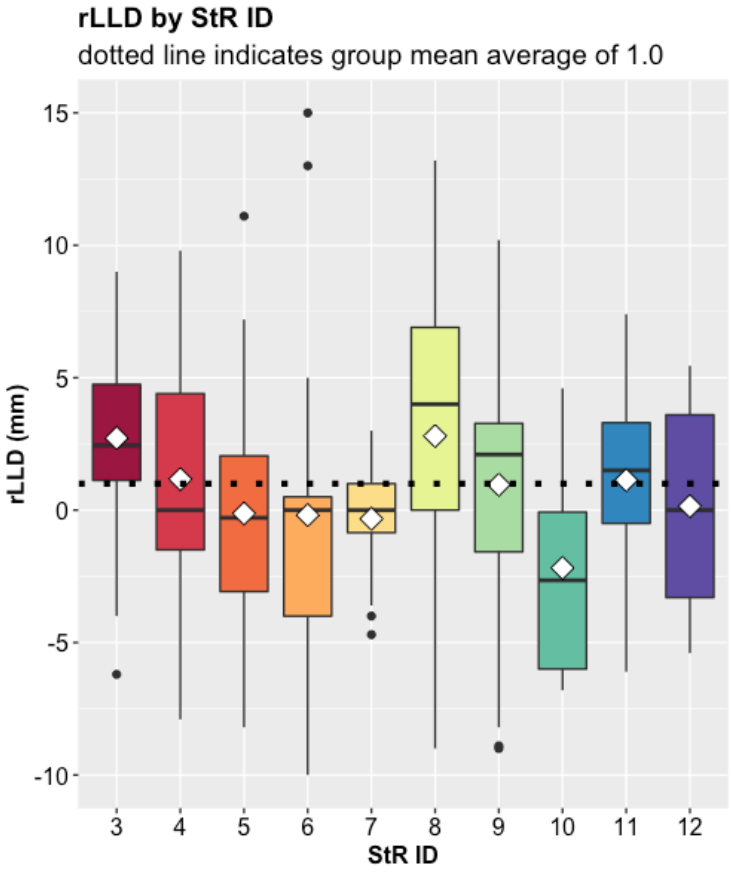


2.4.3.2 Radiological leg length discrepancy (rLLD)

The group mean post-operative rLLD in comparison to the contralateral leg was 1.0mm (range -10.0 - 15.4mm, SD 4.6mm). A significant difference was observed between the StRs individual summary placement rLLD ($p<0.01$). No significant difference in rLLD was found at a group or individual level between placement halves. No significant overall group difference in rLLD was noted according to the level of supervision or surgical assistant grade.

Figure 2-5: Boxplot demonstrating the distribution of rLLD for each StR.

The dotted line represents the mean group rLLD, and the diamond indicates mean rLLD per StR.

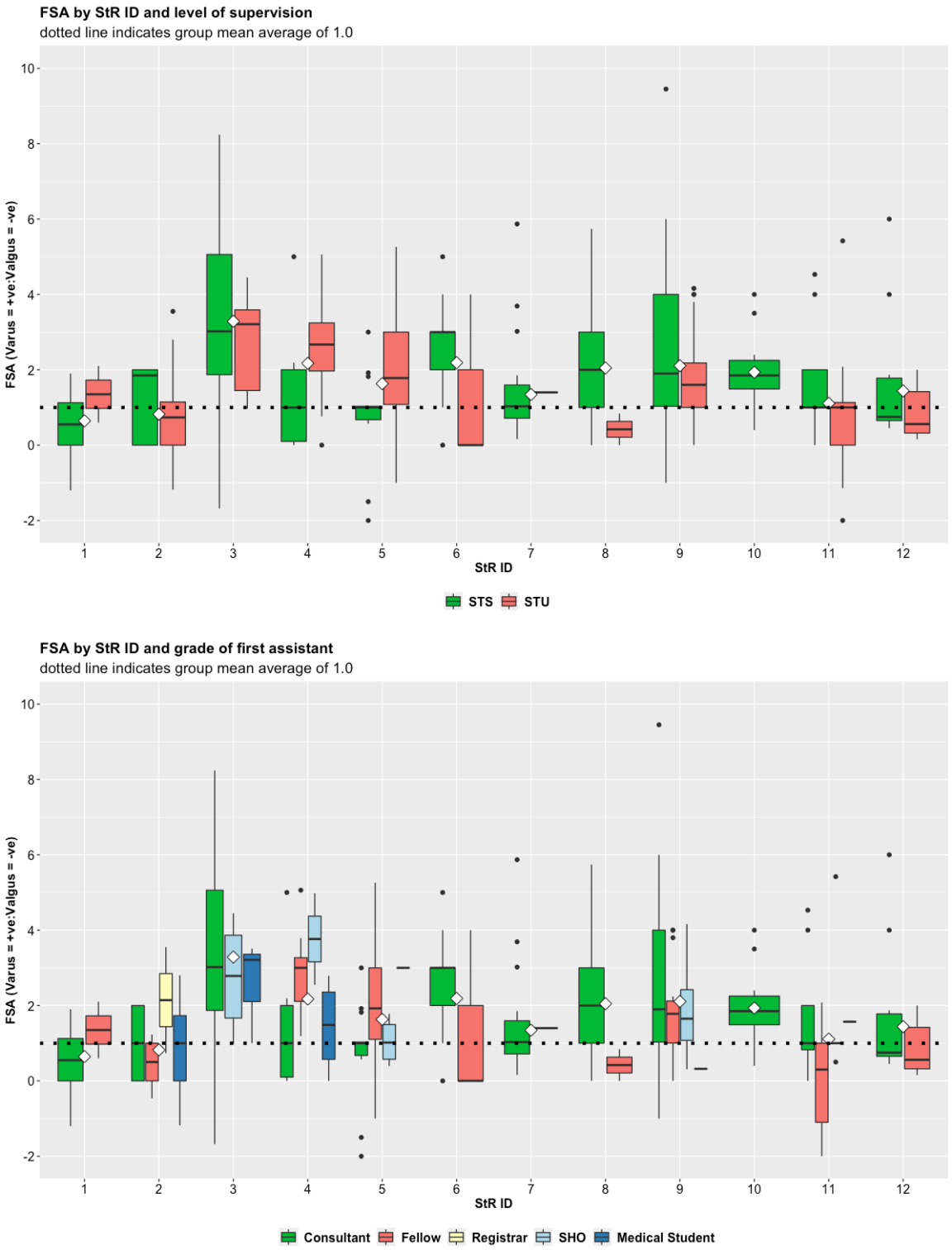


2.4.3.3 Femoral stem alignment (FSA) in the coronal plane

The mean radiographic FSA for all cases was 1.8° varus. A significant difference was observed between the StRs individual summary placement FSA ($p<0.01$). No significant difference in FSA was found at a group or individual level between placement halves. No significant overall group difference in FSA was noted according to the level of supervision or grade of surgical assistant. However, two StRs (#4 and #5) were observed to have significantly less varus FSA when STS in comparison to STU ($p=0.03$ and 0.01, respectively), and a significant difference in the FSA according to the grade of surgical assistant ($p=0.04$ and 0.02, respectively). StR # 4 had significantly higher varus FSA when assisted by an StR (3.8°, SD 1.7) or fellow (2.9°, SD 1.1), in comparison to an SHO (1.4°, SD 1.3) or consultant (1.3°, SD 1.6), and StR # 5 had significantly higher varus FSA when assisted by a fellow (2.1°, SD 1.6), in comparison to an StR (1.1°, SD 0.6) or consultant (0.8°, SD 1.3).

Figure 2-6: Stacked boxplots demonstrating the distribution of FSA for each StR in relation to the level of supervision and grade of first assistant.

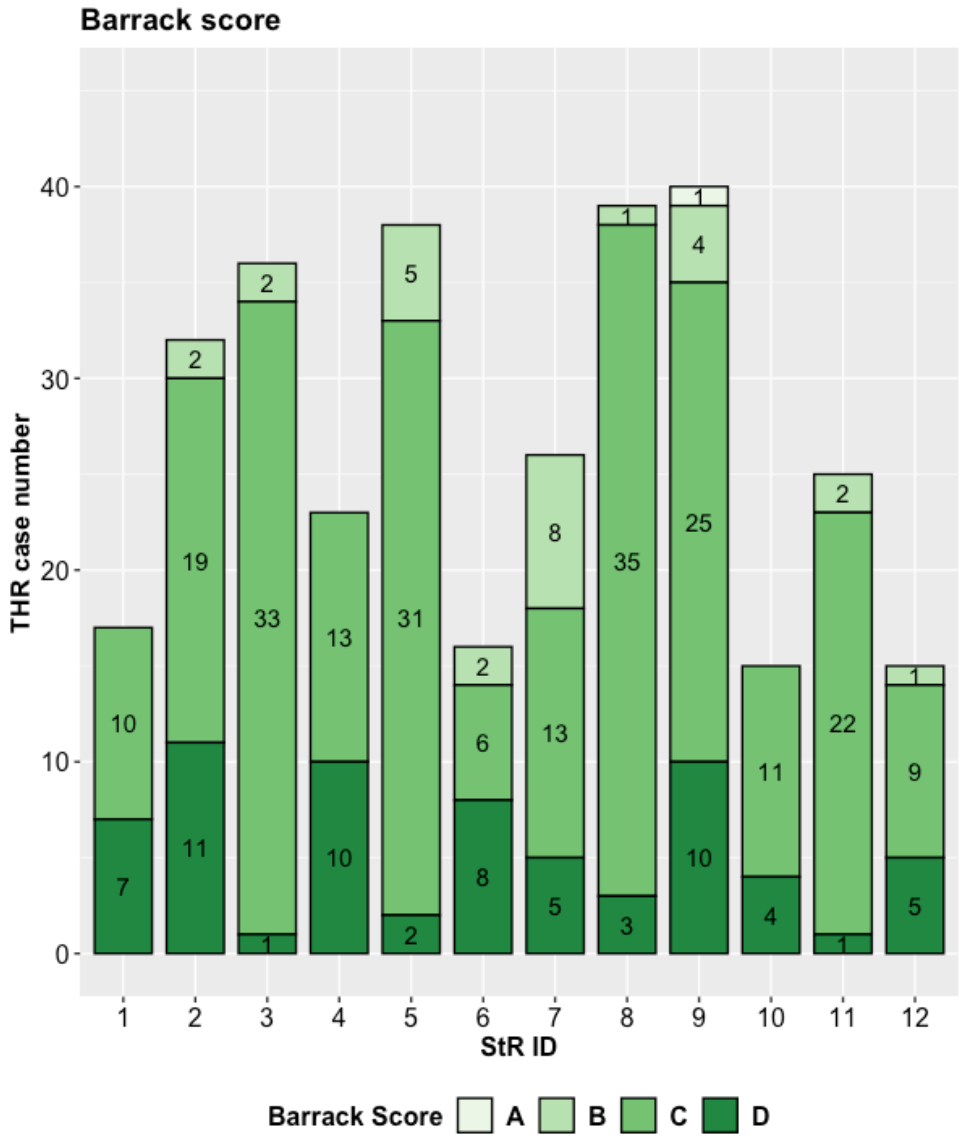
The dotted line on each boxplot represents the mean group FSA, and the diamond indicates mean FSA per StR.



2.4.3.4 Barrack score for quality of femoral cementation

The median Barrack score for quality of femoral cementation was B (n=227, 70.5%). A significant difference was observed between the StRs individual summary placement Barrack scores ($p<0.01$). No significant difference in Barrack scores was observed at an individual level between placement halves. No significant overall group difference in Barrack score was noted according to the level of supervision or grade of surgical assistant.

Figure 2-7: Stacked bar plots demonstrating the Barrack score for quality of femoral cementation for each StR.



2.5 Discussion

2.5.1 Summary and relevance of findings

The results of this study provide a benchmark in orthopaedic surgical trainee performance metrics in primary elective THR, including operative times and radiographic parameters. However, these metrics cannot be used in isolation for assessing and defining the technical skills performance and learning curves of trainees in primary THR. Despite a significant difference in operative times between individual StRs, only two StRs (#7 and #9) demonstrated significantly faster operative times between the first and second halves of cases performed, and a single StR (#11) demonstrated significantly slower operative times. Overall, no significant differences were observed between the first and second halves of cases performed during a 6-month placement at a group level. Operative times appear to be influenced by the experience of the first assistant, suggesting that uncertainty in decision-making during critical steps such as acetabular cup placement may have an impact on operative timings. Operative times were observed to be significantly slower when another registrar acted as first assistant. This observation could be due to an open dialogue, lack of clear decision-making capacity or confidence during key steps of the operation. The opposite may be true when registrars are assisted by senior colleagues (fellows and consultants) whose experience and presence may instil greater confidence and decision-making within the registrar performing the operation. Significant variations were found between trainees in cup positioning, rLLD and FSA. These are unlikely to be of any clinical significance due to most acetabular cups being in an accepted 'safe zone' (114) and the rLLD being within an acceptable range. (138, 147) Regarding variations in FSA, although this is a technical observation there is evidence to suggest its clinical impact and implant survivorship. (148) Despite this, postoperative radiographs provide a valuable mechanism of reflection for the trainee to assess whether they have executed the procedure in accordance with their preoperative plan and templating. Reflection has been well established as an important influence on trainee learning and development. (149) The results also provide an insight into the total number of primary THR trainees perform under supervision within a 6-month clinical placement (median 28, range 15-51). It was interesting to note that despite consultant supervisors being scrubbed (STS) in

almost two-thirds of cases performed by trainees (62.1%), this percentage differed significantly between individual trainees (15.6-94.9%, $p<0.01$). This finding indicates that consultant trainers may feel more comfortable in letting certain (potentially more senior or deemed to be more competent) trainees operate STU, whereas other trainees require a higher level of supervision. The trend for less experienced first assistants in the second half of cases performed by two StRs in this study (#3 and #9) may also indicate progression in performance, as in these cases consultants obviously felt comfortable in letting these trainees operate without close senior supervision. Although patient demographics (age/gender) were not collected as part of this study, the high percentage of hybrid implant fixation (93.1%) used in trainee-led operations indicates an older patient cohort.

Assessing the technical surgical skills and competence of trainees within the UK post-graduate medical education system is based upon completion of PBAs by consultant supervisors. PBAs are an accepted and reliable form of feedback and surgical evaluation (16) but only 53% of orthopaedic trainees find them useful as a feedback method. (54) There are also variations in the application of PBAs. When used as a measure of competence for a specific procedure, the number of cases required to become demonstrate competence using PBAs has been found to vary fourfold. (150) Furthermore, the number of observations from surgical trainers to ensure the surgical autonomy of the trainee has been noted to be significantly higher than current guidelines. (151) The L-CUSUM scores a procedure against a predefined set of criteria and is registered with every procedure of that type. This then allows a learning curve to be plotted over time. This is a labour-intensive exercise to complete for every procedure undertaken by the trainee. Supplementing these techniques with objective measurements such as radiographic analysis and operative times can help both the trainer and trainee focus on areas of potential improvement.

2.5.2 Limitations of study

Limitations of this study include the short timeframe of 6 months for data collection for each trainee. This snapshot of their individual performance and learning curve in THR may not accurately reflect the changes over the entirety of their orthopaedic training. Instead of comparing the cases performed in the first and second halves of a sixth month placement, it may be better to assess the performance of an individual during the early and late stages of the orthopaedic training program. This approach may reveal greater improvements in both operative timings and perhaps radiographic parameters achieved by trainees, which reflects their journey along the learning curve in performing primary hip arthroplasty. The cohort of trainees in this study were at differing levels of experience at the start of their arthroplasty placements, meaning that limited conclusions could be drawn from direct comparisons between trainees. Summary e-logbook data for the entirety of each registrars training program up to the start of this placement was not requested, so the total number of operations, and in particular prior experience in THR was unknown. Furthermore, the outcome measures investigated in this study were not linked to either patient-reported outcome measures (PROMs) or routine validated assessment tools used by the trainees, including PBAs. Owing to the free prose used in learning agreements on Intercollegiate Surgical Curriculum Programme it would be difficult to standardise trainers' comments compared with the objective measures of this study. Finally, the IRR for both FSA and Barrack scoring was only fair, which may limit the interpretation of the results for these parameters.

2.6Conclusions

In conclusion, this retrospective study of primary elective THR operations performed by a cohort of 12 orthopaedic trainees in a single university teaching hospital has demonstrated that operative times and postoperative radiographs cannot be solely used in defining the learning curve and technical skills progression of trainees across a 6-month clinical placement. However, this does not diminish the utility of evaluating postoperative radiographs as a learning aide. The results also provide an insight into the expected number (median 28, range 15-51) and operative times (84.3 minutes, SD 16) of primary THR cases performed by orthopaedic trainees on arthroplasty placements within a 6-month period. Overall, 62.1% of trainee led primary THRs were performed with a scrubbed supervisor (STS), which differed significantly across the cohort of trainees. This finding suggests that consultants adjust their level of supervision for each trainee, which in turn, likely depends upon the skill and ability demonstrated by individual trainees. The impact of supervision in relation to adverse outcomes in trainee led primary THR is investigated in further detail in chapter 3.

3. Defining the incidence of adverse patient outcomes following elective primary total hip replacement

The National Joint Registry (NJR) of England, Wales, and Northern Ireland was established in 2002 by the Department of Health and started to record hip and knee procedures in April 2003. The original purpose of the NJR was to monitor the performance of joint replacements (hip, knee, ankle, elbow, shoulder) used across the United Kingdom and provide early warning of any emerging patient safety issues. However, the NJR may also be used for research purposes aimed at improving clinical practice, patient outcomes and monitoring the performance of clinicians at both an individual, and unit level. To date over 1.25 million primary THR procedures have been recorded on the NJR. (98) The quantity and longevity of NJR data is useful for determining the incidence of rare adverse events following operations, such as revision procedures and mortality. Concerns have previously been raised regarding the potential negative impact of trainee involvement on the incidence of post-operative complications in orthopaedic surgery. (30, 152, 153) The purpose of this study is to investigate the incidence of early and potentially avoidable serious adverse patient outcomes following primary elective THR in relation to the lead surgeon grade and level of trainee supervision. A period of 1-year following primary THR was used as the threshold to determine the early outcomes in this study. The null hypothesis is that no significant differences exist in the incidence of revision or patient mortality within 1-year of elective primary THR for operations performed by consultants or trainees, or according to the level of trainee supervision.

3.1 Aims

The aims of this study are to:

1. Investigate the incidence of early and potentially avoidable serious adverse patient outcomes following primary elective THR.
2. To determine the impact of lead surgeon grade and the level of supervision on these outcome measures.
3. Define any temporal changes in these outcome measures and indications for performing early revisions.

3.2 Methods

Dataset and Ethical Approval

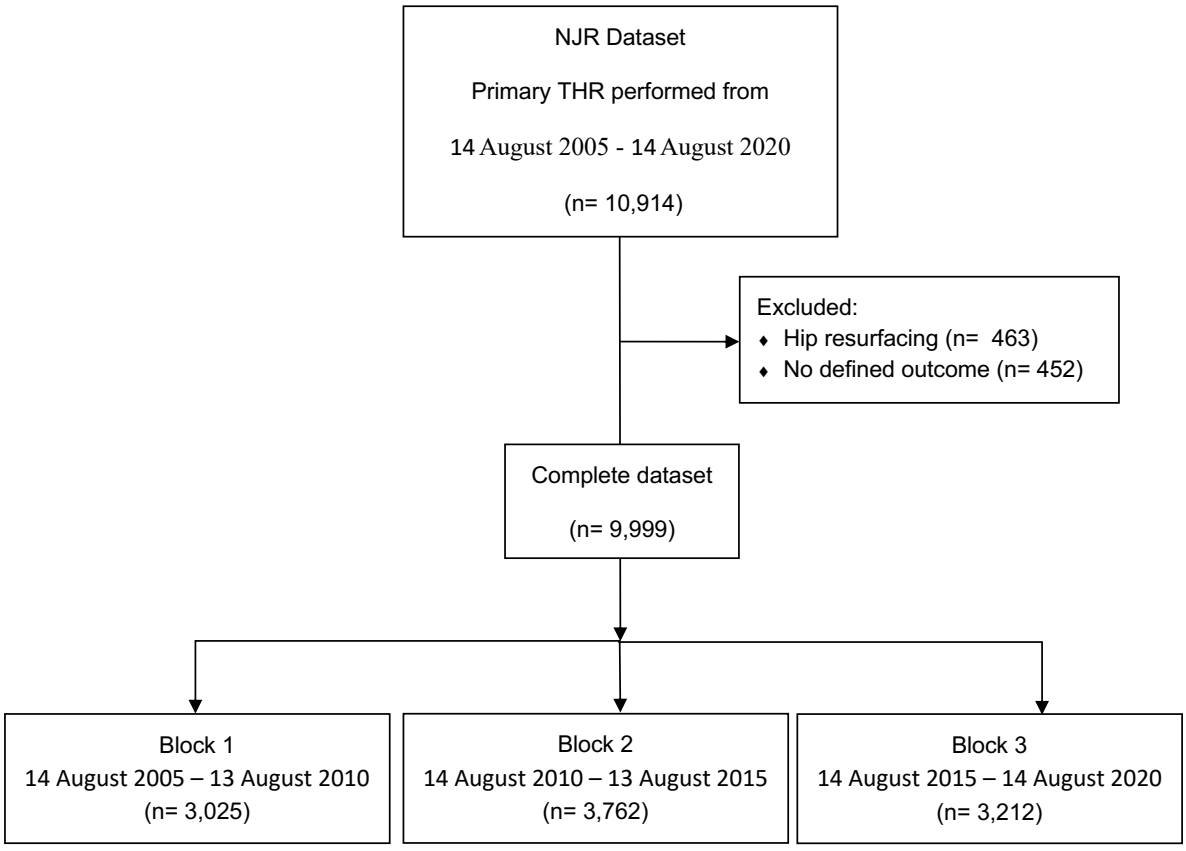
Institutional and NJR approval was granted to access data on patients who underwent elective primary THR within a single high-volume university teaching hospital from 14 August 2006 to 14 August 2021. The unique patient hospital medical record number (MRN) allowed linking of data from the generic NJR H1 (primary hip) and H2 (revision hip) forms. Patient outcomes in this dataset were categorized as unrevised, revised, mortality, and unknown. Cases with unknown outcomes were removed prior to analysis (n=452). The 1-year outcome for each patient was defined as the first event recorded within 366 days of primary elective THR. Only data for primary hybrid, cemented, and uncemented implant fixation combinations were included. Hip resurfacing operations (n=463) were excluded to avoid skewing outcomes, as these are associated with an increased risk of early failure requiring revision surgery (154, 155, 156, 157)

Data cleaning

The lead operating surgeon grade was categorized as consultant-led (CL) or trainee-led (TL) for each case. For the purposes of this study any grade of surgeon apart from consultants were grouped as trainees. The first assistant grade is categorized as ‘consultant’ or ‘other’ on both NJR forms. Any TL operation with a consultant registered as first assistant was categorized as trainee-supervised

(TS), and as trainee-unsupervised (TU) if performed without a consultant as first assistant. Patient age and body mass index (BMI) data were transformed from continuous into categorical variables using 10-year age ranges and standard BMI categories for reporting patient demographics, but were treated as continuous variables in the logistic regression models. (158) Patient American Society of Anesthesiologist (ASA) physical status grades were re-classified into two chunked down groups for reporting demographics and in the logistic regression models. (159) These groups represented healthy patients or those with mild systemic disease (ASA I/II), and those with severe systemic disease which may threaten life (ASA III/IV). Data analysis was performed on the 15-year dataset and split 5-year blocks (B1= 14 August 2005 – 13 August 2010; B2 = 14 August 2010 – 13 August 2015; B3 = 14 August 2015 - 14 August 2020) to determine any temporal trends in patient outcomes. Patients required a minimum of 1-year follow-up after primary THR to be eligible for inclusion.

Figure 3-1: Flow diagram outlining case selection.



Data analysis

Survival analyses were performed separately for 1-year patient mortality or all-cause revision outcomes in relation to both lead surgeon grade (TL/CL) and the level of supervision (TS/TU). (160) Kaplan-Meier (K-M) survival estimate plots are used to visualize outcomes, and log-rank tests used to determine any significant difference in survival between the independent groups tested (lead surgeon grade and level of supervision). (161) Multivariate logistic regression models are used to investigate factors associated with these outcome measures, including patient demographics (age, BMI, gender, ASA grade), and implant fixation as covariates. Descriptive statistics are used to report patient demographic data. Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed between categorical variables. The significance threshold was set at 0.05 for all statistical analysis. Statistical analysis and graphical visualisation were performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA).

3.3 Results

3.3.1 Patient demographics and implant fixation

A total of 9,999 primary THR were recorded between 14 August 2006 to 14 August 2021. Overall, hybrid implant fixation combinations were the most used, representing 73.35% of all cases. Significant temporal changes in implant fixation combinations were observed across the three 5-year blocks, with a trend for decreasing use of cemented, increasing use of uncemented, and a relatively consistent use of hybrid implant fixation (χ^2 $p<0.001$). The median average patient age was 70 years old, with the 61 to 80-year-old age category representing the largest overall with 62.4% of patients. Significant temporal changes in patient age categories were observed across the three 5-year blocks, with an increasing percentage of patients from younger (41-60 years old) and older (81-100 years old) age groups emerging at the expense of those within the commonest age group (61-80 years old) (χ^2 $p<0.001$). The median average patient BMI was 27kg/m^2, with 38.3% of patients falling within the overweight category (BMI 25-29.9kg/m^2). The BMI value was not recorded in a significant proportion of cases (n=1624, 16.2%), but this has consistently improved over the three 5-year blocks (B1= 41.5%; B2= 6.2%; B3= 4.2%). No significant temporal changes were observed in patient BMI categories across the three 5-year blocks. Females represented the highest percentage of patients at 61.2% overall, and no significant temporal changes were observed in patient gender across the three 5-year blocks. Overall, 77.8% of patients were ASA I/II, and significant temporal changes in ASA grades were observed across the three 5-year blocks, with a trend for an increasing number of ASA grade III/IV (χ^2 $p<0.001$).

Table 3-1: Temporal changes in patient demographics and implant fixation in primary THR.

Patient Demographics/Implant Fixation					
Variable	**Overall**, N = 9,999[1]	**B1: 2005-2010, N=3,025**[1]	**B2: 2010-2015, N=3,762**[1]	**B3: 2015-2020, N=3,212**[1]	**p-value**[2]
Implant Fixation					**<0.001**
Hybrid THR	7,334 (73.35%)	2,149 (71.04%)	2,806 (74.59%)	2,379 (74.07%)	
Cemented THR	1,496 (14.96%)	745 (24.63%)	502 (13.34%)	249 (7.75%)	
Uncemented THR	1,169 (11.69%)	131 (4.33%)	454 (12.07%)	584 (18.18%)	
Age					**<0.001**
<20	21 (0.21%)	7 (0.23%)	8 (0.21%)	6 (0.19%)	
21-40	345 (3.45%)	98 (3.24%)	127 (3.38%)	120 (3.74%)	
41-60	1,926 (19.26%)	510 (16.86%)	744 (19.78%)	672 (20.92%)	
61-80	6,243 (62.44%)	1,998 (66.05%)	2,364 (62.84%)	1,881 (58.56%)	
81-100	1,464 (14.64%)	412 (13.62%)	519 (13.80%)	533 (16.59%)	
BMI					0.5
Underweight	119 (1.42%)	18 (1.02%)	59 (1.67%)	42 (1.36%)	
Normal	2,130 (25.43%)	447 (25.27%)	904 (25.62%)	779 (25.32%)	
Overweight	3,207 (38.29%)	710 (40.14%)	1,317 (37.32%)	1,180 (38.35%)	
Obese	2,667 (31.84%)	545 (30.81%)	1,139 (32.28%)	983 (31.95%)	
Morbidly Obese	252 (3.01%)	49 (2.77%)	110 (3.12%)	93 (3.02%)	
Unknown	1,624	1,256	233	135	
Gender					0.2
Female	6,117 (61.18%)	1,877 (62.05%)	2,263 (60.15%)	1,977 (61.55%)	
Male	3,882 (38.82%)	1,148 (37.95%)	1,499 (39.85%)	1,235 (38.45%)	
ASA					**<0.001**
1/2	7,782 (77.83%)	2,320 (76.69%)	3,003 (79.82%)	2,459 (76.56%)	
3/4	2,217 (22.17%)	705 (23.31%)	759 (20.18%)	753 (23.44%)	

[1] n (%)

[2] Pearson's Chi-squared test

3.3.2 Lead surgeon grade and level of supervision

Overall, the majority of primary THR were performed by a consultant as lead surgeon (55.3%), with significant temporal increases observed in the proportion performed by trainees (table 3-2). Within the overall 44.7% of cases (n= 4473) performed by trainees, the majority (53.7%) were unsupervised with no consultant assistant recorded (table 3-3). Significant temporal changes in the proportion of supervised trainee led THR were observed, with a gradual but consistent reduction in the proportion of unsupervised operations from 62.4% in B1 (729/1168) to 59.2% in B2 (1051/1775) and 40.8%, in B3 (624/1530).

Table 3-2: Temporal changes in lead surgeon grade and the level of supervision in primary THR.

Lead surgeon grade and level of supervision					
Variable	**Overall**, N = 9,999[1]	**B1: 2005-2010, N=3,025**[1]	**B2: 2010-2015, N=3,762**[1]	**B3: 2015-2020, N=3,212**[1]	**p-value**[2]
Lead surgeon grade					**<0.001**
Consultant	5,526 (55.27%)	1,857 (61.39%)	1,987 (52.82%)	1,682 (52.37%)	
Trainee	4,473 (44.73%)	1,168 (38.61%)	1,775 (47.18%)	1,530 (47.63%)	
Level of supervision					**<0.001**
Consultant	5,526 (55.27%)	1,857 (61.39%)	1,987 (52.82%)	1,682 (52.37%)	
Supervised Trainee	2,069 (20.69%)	439 (14.51%)	724 (19.25%)	906 (28.21%)	
Unsupervised Trainee	2,404 (24.04%)	729 (24.10%)	1,051 (27.94%)	624 (19.43%)	

[1] n (%)
[2] Pearson's Chi-squared test

Table 3-3: Temporal changes in the level of supervision in trainee led primary THR.

Level of supervision in trainee led operations					
Variable	**Overall**, N = 4,473[1]	**B1: 2005-2010, N=1,168**[1]	**B2: 2010-2015, N=1,775**[1]	**B3: 2015-2020, N=1,530**[1]	**p-value**[2]
Level of supervision					**<0.001**
Supervised Trainee	2,069 (46.26%)	439 (37.59%)	724 (40.79%)	906 (59.22%)	
Unsupervised Trainee	2,404 (53.74%)	729 (62.41%)	1,051 (59.21%)	624 (40.78%)	

[1] n (%)
[2] Pearson's Chi-squared test

3.3.3 Incidence of 1-year mortality and all-cause revision

The overall incidence of 1-year mortality was 2.05% (n= 205), and 1-year all-cause revision was 1.11% (n= 111). There was no significant difference in the overall incidence of 1-year mortality or all-cause revision with respect to the lead surgeon grade (χ^2 p= 0.2 for both outcomes), or level of supervision (χ^2 p= 0.3 for mortality and 0.5 for revision). Significant temporal differences were observed in the incidence of 1-year mortality, with a 2.8% incidence in B1 (86/3025), 1.7%% in B2 (64/3762) and 1.71% in B3 (55/3212) (χ^2 p<0.001). Significant differences in the incidence of 1-year mortality were also observed in relation to: implant fixation (0.6% in uncemented, 1.4% in hybrid, 6.35% in cemented); patient age (1.45% in 21-40, 1.56% in 41-60, 1.65% in 61-80, and 4.58% in 81-100 year olds), BMI (3.36% in underweight, 2.02% in normal, 1.59% in overweight, 1.42% in obese, and 1.59% in morbidly obese patients), gender (1.68% in females and 2.63% in males), and ASA (0.94% in group I/II, and 5.95% in group III/IV). No significant differences were observed in the incidence of 1-year all-cause revision in relation to any patient demographic variables.

Table 3-4: Incidence of 1-year patient mortality and all-cause revision in relation to surgeon grade and supervision, implant fixation, and patient demographics.

	Mortality			Revision		
Variable	**Alive[1]**	**Mortality[1]**	**p-value[2]**	**Not revised[1]**	**Revised[1]**	**p-value[2]**
Block			**0.001**			0.2
2005-2010	2,939 (97.16%)	86 (2.84%)		2,992 (98.91%)	33 (1.09%)	
2010-2015	3,698 (98.30%)	64 (1.70%)		3,728 (99.10%)	34 (0.90%)	
2015-2020	3,157 (98.29%)	55 (1.71%)		3,168 (98.63%)	44 (1.37%)	
Lead Surgeon Grade			0.2			0.2
Consultant	5,403 (97.77%)	123 (2.23%)		5,471 (99.00%)	55 (1.00%)	
Trainee	4,391 (98.17%)	82 (1.83%)		4,417 (98.75%)	56 (1.25%)	
Supervision			0.3			0.5
Consultant	5,403 (97.77%)	123 (2.23%)		5,471 (99.00%)	55 (1.00%)	
Supervised Trainee	2,028 (98.02%)	41 (1.98%)		2,043 (98.74%)	26 (1.26%)	
Unsupervised Trainee	2,363 (98.29%)	41 (1.71%)		2,374 (98.75%)	30 (1.25%)	
Implant Fixation			**<0.001**			0.4
Hybrid THR	7,231 (98.60%)	103 (1.40%)		7,247 (98.81%)	87 (1.19%)	
Cemented THR	1,401 (93.65%)	95 (6.35%)		1,484 (99.20%)	12 (0.80%)	
Uncemented THR	1,162 (99.40%)	7 (0.60%)		1,157 (98.97%)	12 (1.03%)	
Age			**<0.001**			0.2
61-80	6,140 (98.35%)	103 (1.65%)		6,181 (99.01%)	62 (0.99%)	
<20	21 (100.00%)	0 (0.00%)		20 (95.24%)	1 (4.76%)	
21-40	340 (98.55%)	5 (1.45%)		342 (99.13%)	3 (0.87%)	
41-60	1,896 (98.44%)	30 (1.56%)		1,899 (98.60%)	27 (1.40%)	
81-100	1,397 (95.42%)	67 (4.58%)		1,446 (98.77%)	18 (1.23%)	
BMI			0.3			**0.001**
Normal	2,087 (97.98%)	43 (2.02%)		2,118 (99.44%)	12 (0.56%)	
Underweight	115 (96.64%)	4 (3.36%)		119 (100.00%)	0 (0.00%)	
Overweight	3,156 (98.41%)	51 (1.59%)		3,167 (98.75%)	40 (1.25%)	
Obese	2,629 (98.58%)	38 (1.42%)		2,636 (98.84%)	31 (1.16%)	
Morbidly Obese	248 (98.41%)	4 (1.59%)		243 (96.43%)	9 (3.57%)	
Unknown	1,559	65		1,605	19	
Gender			**0.001**			0.3
Female	6,014 (98.32%)	103 (1.68%)		6,054 (98.97%)	63 (1.03%)	
Male	3,780 (97.37%)	102 (2.63%)		3,834 (98.76%)	48 (1.24%)	
ASA			**<0.001**			0.14
1/2	7,709 (99.06%)	73 (0.94%)		7,702 (98.97%)	80 (1.03%)	
3/4	2,085 (94.05%)	132 (5.95%)		2,186 (98.60%)	31 (1.40%)	

[1] n (%)

[2] Pearson's Chi-squared test; Fisher's exact test

3.3.4 The effect of lead surgeon grade on 1-year mortality and all-cause revision

Mortality

For CL operations the overall incidence of 1-year patient mortality was 2.23% (n= 123), in comparison to 1.83% (n= 82) in TL operations. Multivariate logistic regression modelling did not identify any significant differences in the incidence of 1-year patient mortality between CL and TL operations overall (OR = 0.78, 95% CI 0.55–1.10, p= 0.2), or within any 5-year block. K-M and log-rank analysis did not identify any significant difference in 1-year patient mortality between CL and TL operations overall (p= 0.18) or within any 5-year block.

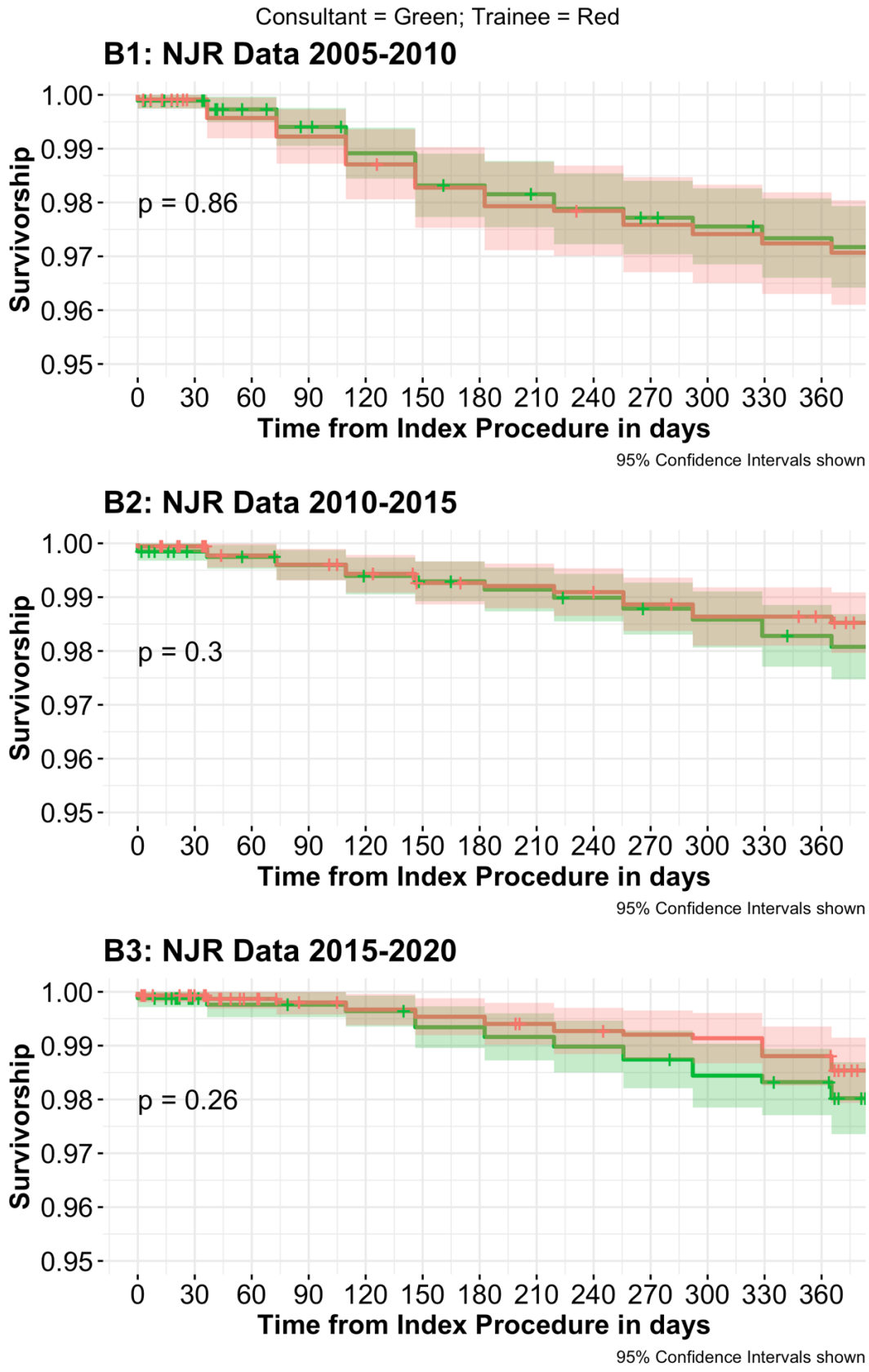
Table 3-5: Multivariate logistic regression for 1-year patient mortality following primary THR in relation to lead surgeon grade.

Patient demographic and implant fixation covariates.

	Overall			B1: 2005-2010			B2: 2010-2015			B3: 2015-2020		
Variable	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**
Lead Surgeon												
Consultant	—	—		—	—		—	—		—	—	
Trainee	0.78	0.55, 1.10	0.2	1.57	0.73, 3.35	0.2	0.58	0.33, 1.01	0.054	0.69	0.39, 1.21	0.2
Implant Fixation												
Hybrid THR	—	—		—	—		—	—		—	—	
Cemented THR	2.94	2.03, 4.24	**<0.001**	4.60	2.05, 11.0	**<0.001**	2.48	1.32, 4.54	**0.004**	3.51	1.83, 6.55	**<0.001**
Uncemented THR	0.48	0.14, 1.20	0.2	7.72	1.10, 34.6	**0.015**	0.00	0.00, 732	>0.9	0.33	0.05, 1.21	0.15
Age	1.01	1.00, 1.03	0.11	1.02	0.98, 1.06	0.4	1.02	1.00, 1.05	0.11	1.00	0.98, 1.03	>0.9
BMI	0.97	0.94, 1.00	0.069	1.01	0.94, 1.07	0.7	0.96	0.91, 1.01	0.12	0.96	0.91, 1.01	0.11
Gender												
Female	—	—		—	—		—	—		—	—	
Male	1.56	1.10, 2.19	**0.012**	1.55	0.73, 3.27	0.2	1.72	0.99, 2.99	0.053	1.55	0.88, 2.72	0.12
ASA												
1/2	—	—		—	—		—	—		—	—	
3/4	5.70	3.98, 8.27	**<0.001**	4.36	2.03, 9.71	**<0.001**	4.97	2.84, 8.82	**<0.001**	8.03	4.33, 15.7	**<0.001**

[1] OR = Odds Ratio, CI = Confidence Interval

Figure 3-2: Kaplan-Meier survival plots of 1-year patient mortality in relation to lead surgeon grade across the three 5-year blocks.



Revision

For CL operations the overall incidence of 1-year all-cause revision was 1.01% (n= 55) in comparison to 1.27% (n= 56) in TL operations. Multivariate logistic regression modelling did not identify any significant differences in the incidence of 1-year patient all-cause revision between CL and TL operations overall (OR = 1.37, 95% CI 0.89–2.09, p= 0.15), or within any 5-year block. K-M and log-rank analysis did not identify any significant difference in 1-year patient all-cause revision between CL and TL operations overall (p= 0.23) or within any 5-year block.

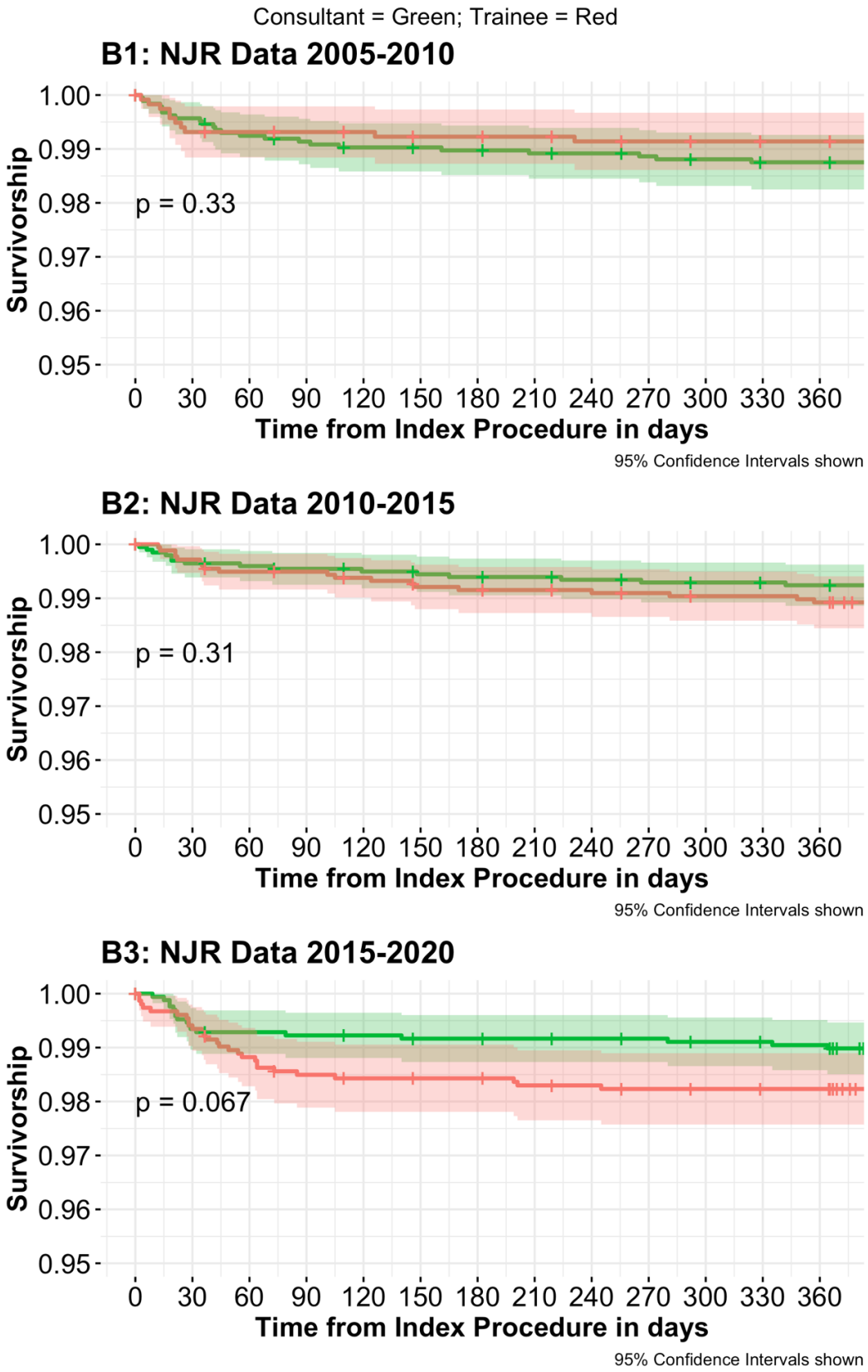
Table 3-6: Multivariate logistic regression results for 1-year patient all-cause revision following primary THR in relation to lead surgeon grade.

Patient demographics and implant fixation covariates.

	Overall			B1: 2005-2010			B2: 2010-2015			B3: 2015-2020		
Variable	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**
Lead Surgeon												
Consultant	—	—		—	—		—	—		—	—	
Trainee	1.37	0.89, 2.09	0.15	0.71	0.24, 1.80	0.5	1.51	0.71, 3.28	0.3	1.84	0.97, 3.63	0.068
Implant Fixation												
Hybrid THR	—	—		—	—		—	—		—	—	
Cemented THR	0.89	0.44, 1.64	0.7	0.13	0.01, 0.65	0.050	1.50	0.42, 4.15	0.5	2.06	0.74, 4.87	0.13
Uncemented THR	0.77	0.35, 1.52	0.5	0.90	0.05, 4.92	>0.9	1.17	0.37, 3.13	0.8	0.54	0.15, 1.62	0.3
Age	0.99	0.97, 1.01	0.2	1.00	0.96, 1.04	>0.9	0.97	0.94, 1.00	**0.040**	0.99	0.97, 1.03	0.7
BMI	1.04	1.01, 1.07	**0.005**	1.04	0.97, 1.08	0.2	1.05	0.99, 1.11	0.079	1.04	0.99, 1.09	0.066
Gender												
Female	—	—		—	—		—	—		—	—	
Male	1.21	0.79, 1.83	0.4	0.79	0.30, 1.93	0.6	1.57	0.76, 3.28	0.2	1.31	0.69, 2.44	0.4
ASA												
1/2	—	—		—	—		—	—		—	—	
3/4	1.61	1.00, 2.52	**0.044**	2.27	0.87, 5.61	0.079	1.28	0.49, 2.97	0.6	1.43	0.70, 2.81	0.3

[1] OR = Odds Ratio, CI = Confidence Interval

Figure 3-3: Kaplan-Meier survival plots of 1-year patient all-cause revision in relation to lead surgeon grade across the three 5-year blocks.



3.3.5 The effect of trainee supervision on 1-year mortality and all-cause revision

Mortality

For TS operations the overall incidence of 1-year patient mortality was 1.98% (n= 41), in comparison to 1.71% (n= 41) in TU operations. Multivariate logistic regression modelling did not identify any significant differences in the overall incidence of 1-year patient mortality between consultant and TS (OR = 0.63, 95% CI 0.29–1.26, p= 0.2), or between consultant and TU operations (OR = 0.55, 95% CI 0.28–1.04, p= 0.072). No significant differences in the incidence of 1-year patient mortality were found between consultant and TS or TU within any of the 5-year blocks. K-M and log-rank analysis did not identify any significant difference in the incidence of 1-year patient mortality between consultant and TS or TU operations overall (p= 0.32) or within any 5-year block.

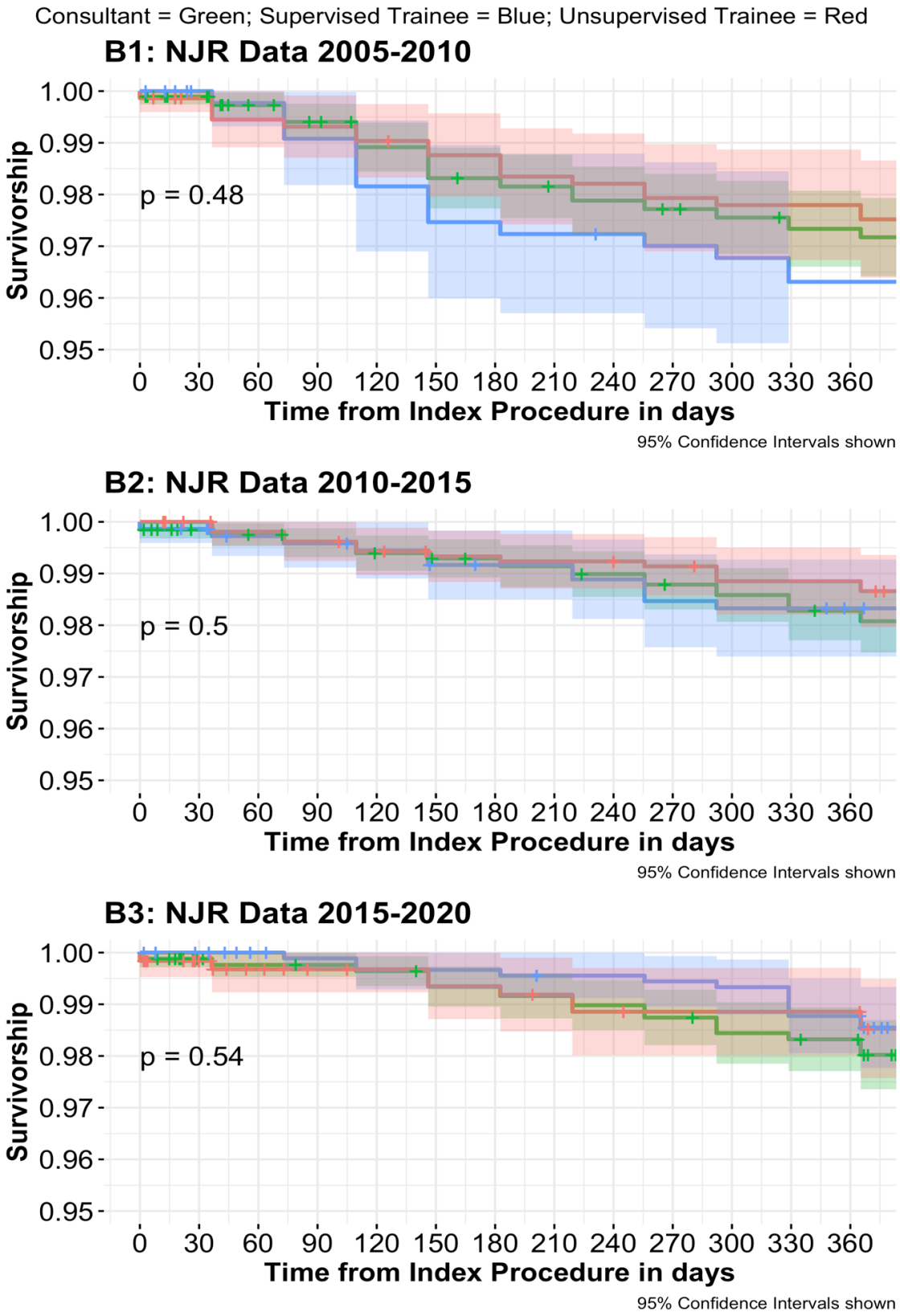
Table 3-7: Multivariate logistic regression for 1-year patient mortality following primary THR in relation to the level of supervision.

Patient demographics and implant fixation covariates.

	Overall			B1: 2005-2010			B2: 2010-2015			B3: 2015-2020		
Variable	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**
Surgeon Combination												
Consultant	—	—		—	—		—	—		—	—	
Supervised Trainee	0.87	0.56, 1.32	0.5	2.12	0.82, 5.08	0.10	0.72	0.36, 1.37	0.3	0.72	0.36, 1.37	0.3
Unsupervised Trainee	0.70	0.45, 1.07	0.11	1.20	0.45, 2.97	0.7	0.66	0.29, 1.37	0.3	0.66	0.29, 1.37	0.3
Implant Fixation												
Hybrid THR	—	—		—	—		—	—		—	—	
Cemented THR	2.97	2.04, 4.28	**<0.001**	4.62	2.06, 11.1	**<0.001**	3.52	1.83, 6.57	**<0.001**	3.52	1.83, 6.57	**<0.001**
Uncemented THR	0.48	0.14, 1.20	0.2	7.63	1.08, 34.1	**0.015**	0.33	0.05, 1.21	0.15	0.33	0.05, 1.21	0.15
Age	1.01	1.00, 1.03	0.11	1.02	0.98, 1.06	0.4	1.00	0.98, 1.03	>0.9	1.00	0.98, 1.03	>0.9
BMI	0.97	0.94, 1.00	0.070	1.01	0.94, 1.07	0.7	0.96	0.91, 1.01	0.11	0.96	0.91, 1.01	0.11
Gender												
Female	—	—		—	—		—	—		—	—	
Male	1.56	1.10, 2.20	**0.012**	1.55	0.73, 3.26	0.2	1.56	0.88, 2.72	0.12	1.56	0.88, 2.72	0.12
ASA												
1/2	—	—		—	—		—	—		—	—	
3/4	5.71	3.98, 8.27	**<0.001**	4.34	2.02, 9.71	**<0.001**	8.04	4.33, 15.8	**<0.001**	8.04	4.33, 15.8	**<0.001**

[1] OR = Odds Ratio, CI = Confidence Interval

Figure 3-4: Kaplan-Meier survival plots of 1-year patient mortality in relation to the level of supervision across the three 5-year blocks.



Revision

For TS operations the overall incidence of 1-year all-cause revision was 1.27% (n= 26) in comparison to 1.26% (n= 30) in TU operations. Multivariate logistic regression modelling did not identify any significant differences in the overall incidence of 1-year patient all-cause revision between TS (OR = 1.39, 95% CI 0.82–2.30, p= 0.2) and TU operations (OR = 1.35, 95% CI 0.80–2.22, p= 0.3) in comparison to CL operations. However, a significantly increased incidence of 1-year all-cause revision was identified between TU and CL operations only in block 3 data from 2015-2020 (OR = 2.81, 95% CI 1.35–5.87, p= 0.005). The incidence of 1-year all-cause revision in TU operations from 2015-2020 was 2.72% (17/624), in comparison to 1.1% (10/906) in TS, and 1.01% (17/1682) in CL operations. The incidence of 1-year all-cause revision in TU operations from 2005-2010 was 0.55% (4/729), and 0.86% (9/1051) from 2010-2015. No significant differences were identified in the incidence of 1-year patient all-cause revision between CL and TS operations within any of the 5-year blocks. Although K-M and log-rank analysis did not identify any overall difference in the incidence of 1-year patient all-cause revision between CL, TS, and TU operations (p= 0.48), it did identify the significant difference in block 3 data from 2015-2020 (p= 0.005).

Table 3-8: Incidence of revision within 1-year following primary THR in relation to the surgeon grade and level of trainee supervision.

	Overall[1]	Consultant[1]	Supervised Trainee[1]	Unsupervised Trainee[1]	p-value[2]
Summary: 2005-2020					
					0.5
Not revised	9,888 (98.89%)	5,471 (99.00%)	2,043 (98.74%)	2,374 (98.75%)	
Revised	111 (1.11%)	55 (1.00%)	26 (1.26%)	30 (1.25%)	
B1: 2005-2010					
					0.2
Not revised	2,992 (98.91%)	1,834 (98.76%)	433 (98.63%)	725 (99.45%)	
Revised	33 (1.09%)	23 (1.24%)	6 (1.37%)	4 (0.55%)	
B2: 2010-2015					
					0.3
Not revised	3,728 (99.10%)	1,972 (99.25%)	714 (98.62%)	1,042 (99.14%)	
Revised	34 (0.90%)	15 (0.75%)	10 (1.38%)	9 (0.86%)	
B3: 2015-2020					
					0.005
Not revised	3,168 (98.63%)	1,665 (98.99%)	896 (98.90%)	607 (97.28%)	
Revised	44 (1.37%)	17 (1.01%)	10 (1.10%)	17 (2.72%)	

[1] n (%)

[2] Pearson's Chi-squared test

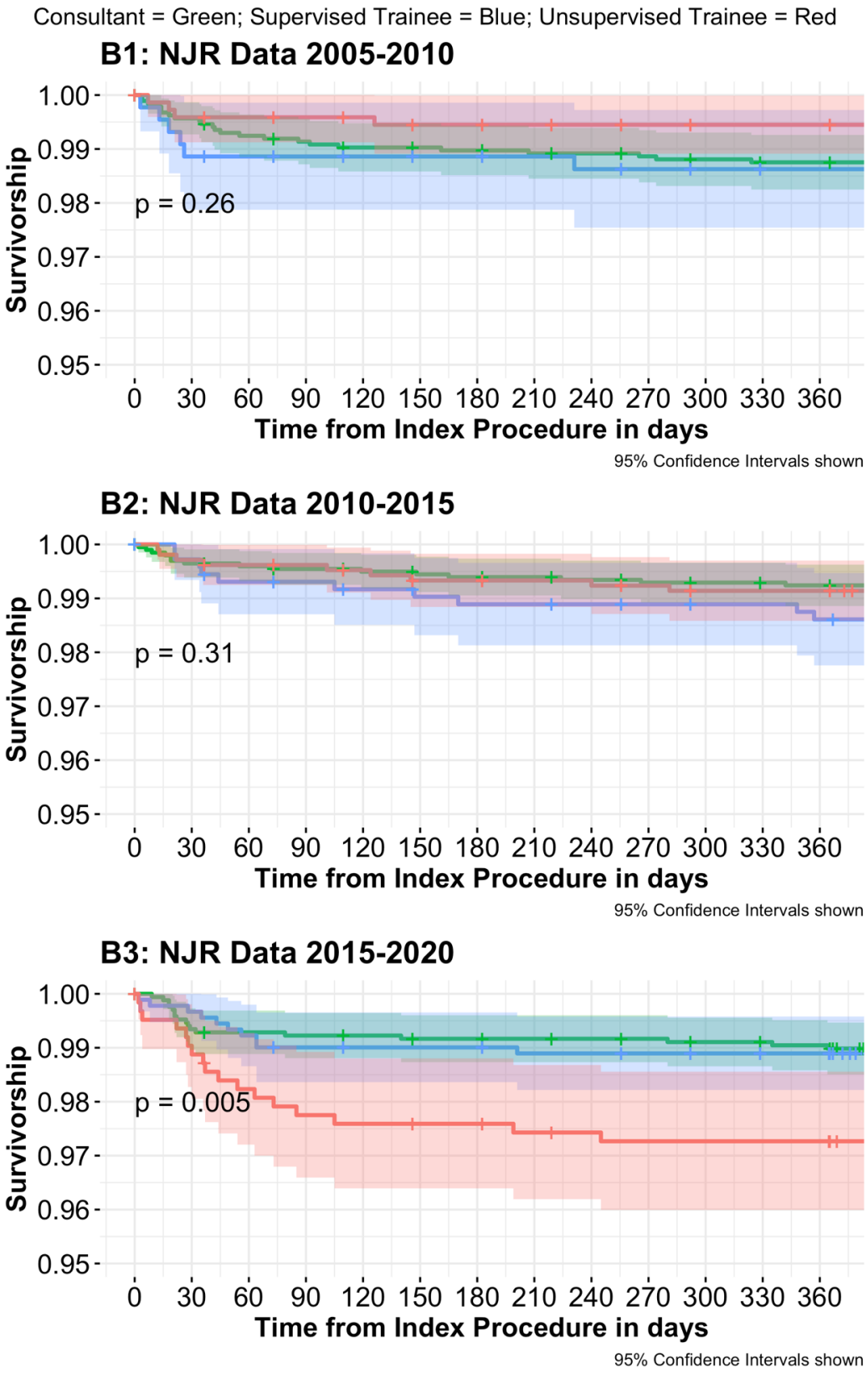
Table 3-9: Multivariate logistic regression for 1-year patient all-cause revision following primary THR in relation to the level of supervision.

Patient demographics and implant fixation covariates.

	Overall			B1: 2005-2010			B2: 2010-2015			B3: 2015-2020		
Variable	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**	**OR[1]**	**95% CI[1]**	**p-value**
Surgeon Combination												
Consultant	—	—		—	—		—	—		—	—	
Supervised Trainee	1.39	0.82, 2.30	0.2	1.60	0.51, 4.26	0.4	1.85	0.72, 4.47	0.2	1.19	0.51, 2.67	0.7
Unsupervised Trainee	1.35	0.80, 2.22	0.3	0.17	0.01, 0.91	0.10	1.28	0.49, 3.11	0.6	2.81	1.35, 5.87	**0.005**
Implant Fixation												
Hybrid THR	—	—		—	—		—	—		—	—	
Cemented THR	0.89	0.44, 1.64	0.7	0.13	0.01, 0.64	**0.048**	1.52	0.43, 4.19	0.5	2.09	0.75, 4.99	0.12
Uncemented THR	0.77	0.36, 1.52	0.5	0.87	0.05, 4.76	0.9	1.19	0.37, 3.17	0.8	0.52	0.14, 1.55	0.3
Age	0.99	0.97, 1.01	0.2	1.00	0.97, 1.04	>0.9	0.97	0.94, 1.00	**0.042**	0.99	0.97, 1.02	0.6
BMI	1.04	1.01, 1.07	**0.005**	1.05	0.98, 1.11	0.12	1.05	0.99, 1.11	0.080	1.04	0.99, 1.09	0.080
Gender												
Female	—	—		—	—		—	—		—	—	
Male	1.21	0.79, 1.83	0.4	0.81	0.30, 1.97	0.6	1.58	0.76, 3.31	0.2	1.29	0.68, 2.41	0.4
ASA												
1/2	—	—		—	—		—	—		—	—	
3/4	1.61	1.00, 2.52	**0.044**	2.07	0.78, 5.18	0.13	1.28	0.49, 2.98	0.6	1.41	0.69, 2.78	0.3

[1] OR = Odds Ratio, CI = Confidence Interval

Figure 3-5: Kaplan-Meier survival plots of 1-year patient all-cause revision in relation to the level of supervision across the three 5-year blocks.



3.3.6 Modes of failure in early revision THR

The current NJR form used to record revision hip procedures (H2 MDS version 7.0) lists 13 indications for the procedure. Although this list is not exhaustive, it contains the most common indications for any revision hip procedure at any time point following primary THR. The modes of failure associated with THR change with respect to the time following primary procedure. As this research focusses on early revisions, defined as taking place within 1 year of primary THR, the NJR list has been reduced to three recognised key indications for undertaking early revision procedures, namely dislocation/instability; peri-prosthetic fracture (PPF); and prosthetic joint infection (PJI). (162) Revisions undertaken for any other indication have been grouped into the category 'other'. Overall, the most common indication for revision procedures within 1-year of primary THR was PJI at 31.53% (35/111), followed closely by dislocation/instability at 29.73% (33/111), all 'other' indications at 20.72% (23/111), and PPF at 18.02% (20/111). Overall, no significant differences were observed in the indication for revision with respect to lead surgeon grade (χ^2 p= 0.74) or level of supervision (χ^2 p= 0.63), or within any of the three 5-year blocks. The significant increased incidence of revisions within 1-year of primary THR observed in TU operations between 2015-2020 appears to be predominantly driven by increases in PJI (n= 7) and dislocation/instability (n= 7), which collectively represented the indication for revision in 82.36% of cases (14/17).

Table 3-10: Indication for undergoing revision within 1-year following primary THR in relation to the level of supervision.

	Overall[1]	Consultant[1]	Supervised Trainee[1]	Unsupervised Trainee[1]	p-value[2]
Summary: 2005-2020					
					0.6
Infection	35 (31.53%)	18 (32.73%)	7 (26.92%)	10 (33.33%)	
Dislocation/Instability	33 (29.73%)	16 (29.09%)	8 (30.77%)	9 (30.00%)	
PPF	20 (18.02%)	8 (14.55%)	4 (15.38%)	8 (26.67%)	
Other	23 (20.72%)	13 (23.64%)	7 (26.92%)	3 (10.00%)	
B1: 2005-2010					
					>0.9
Infection	8 (24.24%)	5 (21.74%)	2 (33.33%)	1 (25.00%)	
Dislocation/Instability	14 (42.42%)	11 (47.83%)	2 (33.33%)	1 (25.00%)	
PPF	5 (15.15%)	3 (13.04%)	1 (16.67%)	1 (25.00%)	
Other	6 (18.18%)	4 (17.39%)	1 (16.67%)	1 (25.00%)	
B2: 2010-2015					
					0.5
Infection	6 (17.65%)	3 (20.00%)	1 (10.00%)	2 (22.22%)	
Dislocation/Instability	7 (20.59%)	3 (20.00%)	3 (30.00%)	1 (11.11%)	
PPF	10 (29.41%)	3 (20.00%)	2 (20.00%)	5 (55.56%)	
Other	11 (32.35%)	6 (40.00%)	4 (40.00%)	1 (11.11%)	
B3: 2015-2020					
					0.5
Infection	21 (47.73%)	10 (58.82%)	4 (40.00%)	7 (41.18%)	
Dislocation/Instability	12 (27.27%)	2 (11.76%)	3 (30.00%)	7 (41.18%)	
PPF	5 (11.36%)	2 (11.76%)	1 (10.00%)	2 (11.76%)	
Other	6 (13.64%)	3 (17.65%)	2 (20.00%)	1 (5.88%)	

[1] n (%)

[2] Fisher's exact test

3.4Discussion

3.4.1 Summary and relevance of findings

One of the most striking findings of this study is the significant temporal increase observed in the incidence of revision procedures within 1-year of primary THR operations performed by unsupervised trainees in comparison to either supervised trainees or consultants between 2015-2020. The indication for these early revisions appears to be predominantly driven by an increased incidence of PJI and dislocation/instability, which are recognised indications for early revision procedures. (20, 162, 163, 164) These findings are supported by the results of another recent observational study using NJR data. (165) The aetiology of these early revisions cannot be determined using this NJR dataset alone, but clearly the lack of consultant supervision of trainees in theatre during primary THR appears to be an important factor. Patients who undergo early revision procedures are reported to have poorer long-term outcomes, and an increased risk of re-revision procedures. (163, 166, 167, 168, 169, 170) This highlights the importance of Getting It Right First Time (GIRFT) to reduce complications, healthcare costs, and optimise patient outcomes following elective orthopaedic surgery. (171) Furthermore, any revision procedures are recorded under the lead consultant NJR figures, which may place them at increased risk of falling into outlier status. The findings of this study therefore have wide ranging implications not only for patients and trainee surgeons, but also for the NJR profiles of consultant trainers. Interestingly, the increased incidence of early revisions in unsupervised trainee-led operations was not seen over the entire 15-year data collection period, or during B1 (2005-2010) and B2 (2010-2015). This suggests that the increased incidence of early revisions in unsupervised trainee led THR is a relatively recent phenomenon. Over the 15-year data period, significant temporal increases have been observed in the proportion of primary THR performed by trainees (χ^2 $p<0.001$), but with a gradual reduction in the proportion of trainee-led operations being unsupervised from 62.4% in B1 to 40.8%, in B3. This proportion of trainee led primary THR is not only much larger than those reported in other studies (20, 21), but also suggests that trainees are performing an increasing proportion of primary THR under supervision. One potential explanation for the increased revision rate may be that trainees since 2015 have overall less

operative experience than their predecessors, which may affect their intra-operative performance, judgement, and incidence of post-operative adverse patient outcomes. However, the total number of THRs performed by each trainee in this data set is unknown, as outcomes have not been linked to individual surgical logbook data. It should, therefore, be noted that the cause of this recent increased incidence of early revision procedures following unsupervised trainee led primary THR is not fully understood, and further research is required to determine the reasons behind this observation.

It is re-assuring to report that no significant differences were identified in the risk of 1-year mortality or all-cause revision between consultant-led, overall trainee-led, or trainee-supervised operations across the entire 15-year data collection period, or within any of the 5-year blocks. This finding supports those of other published studies which have reported no significantly increased risk of revision procedures in patients undergoing THR operations performed by trainees in comparison to consultants. (20, 26, 28, 30, 165, 172, 173) The results of one systematic review and meta-analysis reported no significant difference in revision rates between trainee and consultant led primary THR (OR 1.09, p=0.51). (30) However the time to revision and level of supervision for trainee led operations were not considered within this meta-analysis. Another recent systematic review and meta-analysis of five eligible studies analysed a total of 1464 trainee led THR and 2602 consultant led THR over a 10-year follow-up period. (172) The authors reported a relative risk of revision for trainee led primary THR of 0.88 (95% CI 0.46-1.70) at 5 years, and 0.68 (95% CI 0.37 to 1.26) at 10 years, respectively. A recent large observational study using an NJR dataset of 603474 primary THR reported no association between surgeon grade and all-cause revision up to ten-years, with a hazard ratio of 1.00 (95% CI 0.04-1.07), p=0.966. (165) A significant difference between that study and this is the proportion of trainee-led procedures, with only 9.6% of all primary THR recorded as trainee led (n=58137). Interestingly, the large NJR study only included procedures up to 2016, suggesting the increase in revisions in the latest period of this study has not been investigated.

The strengths of this study include the relatively large proportion of trainee led primary THR (n=4473, 44.7%), a fifteen-year period data collection period, and a minimum of 1-year follow-up

for all patients. This study has also identified several other interesting findings, including an overall incidence of 1-year mortality following THR of 2.05% and 1-year all-cause revision of 1.11%. The 18th annual NJR report quotes an incidence of 0.81% (95% CI 0.79-0.83) in 1-year revision following all primary THR cases (98), which is similar to the findings of this study. It is no surprise that the incidence of 1-year mortality following elective primary THR was highest in older patients with higher ASA grades, and those receiving cemented implant fixation (6.4%) in comparison to hybrid (1.4%) and uncemented (0.6%) implants, as the choice of implant fixation is largely dependent upon age, activity level, and co-morbid status. Interestingly, a higher incidence of 1-year mortality was observed in underweight patients (3.4%) in comparison to overweight (1.6%), obese (1.4%), or even morbidly obese (1.6%) patients. This highlights the mortality risk associated with malnourishment and poor physiological reserves in the surgical patient. The demographics of patients undergoing primary THR in this dataset are representative of patients across the UK as reported in the NJR (98), with 61.2% female patients (59.9% in the NJR), a median average age of 70 years old (median 69 in the NJR), and 77.8% ASA I/II (83.2% in the NJR). The use of hybrid implant fixation was over-represented (overall 73.3%), and both cemented and uncemented fixation under-represented (15.0% and 11.7% overall, respectively) in this study in comparison to NJR figures. (98)

The provision of high-quality training is critically important to ensuring a highly skilled future generation of surgeons, and the results of this study should not be used to reduce surgical training opportunities. The results should however be used as a prompt for surgical trainers and departments to consider the theatre environment, human resources, surgical equipment, and patient case selection which are best suited for providing the optimal surgical training opportunities. Surgical trainees should be supported and encouraged by trainers and healthcare institutions alike to operate within the limits of their competence and always with adequate educational and clinical supervision. Postgraduate medical education and training boards should strongly consider alternative strategies and methods for supporting trainees learning and development outside of the immediate theatre environment. This may include an increased provision of evidence-based surgical simulation training to assist trainees in acquiring and optimising their technical surgical skills performance in the safety

of a non-clinical environment prior before transferring and refining them in theatre under the direct supervision of experienced consultant trainers. (94, 174) Mechanisms to identify and address adverse patient outcomes and complications should be embodied within the clinical governance structure of all healthcare institutions. Departmental morbidity and mortality meetings are one example of a forum where all staff should be encouraged to openly discuss complications without apportioning blame, investigate potential causative factors, and implement positive changes aimed at improving patient care and outcomes. Self-reflection is also an important aspect of continuing professional development, which all surgeons should engage in to identify potential areas for personal improvement.

3.4.2 Limitations of study

As with every registry-based study, the quality of data inputted (to the NJR in this case), directly correlates with the reliability of the results generated. Incorrectly coded or missing data, along with changes in the scope of data collected over time may result in inaccurate interpretations and conclusions. Since its inception back in 2002 the NJR has used several different versions of the H1 and H2 forms for data collection. Version 7 of the NJR minimum data set (MDS) was launched in June 2018. Progressive changes in both the number and detail of options available for recording variables such as the lead surgeon and assistant grade over the years have clearly affected the uniformity of these datasets. In this study a high proportion of missing data entries were noted particularly in relation to BMI. However, this has improved significantly over time. The lead operating surgeon grade was recorded as ‘other’ in 2040 cases (20.4%), which may reflect fellows, as this grade is not accounted for on the NJR H1 form. Speculation exists regarding the transparency in surgeons completing and submitting H2 forms for all revision hip procedures performed, particularly in the early years following establishment of the NJR. Procedures such as debridement, antibiotics, and implant retention (DAIR) which may have previously avoided capture on the NJR, are now being recorded with greater reliability. Furthermore, procedures such as closed reduction of hip dislocations may also avoid capture on the NJR database, which would reduce the overall figure

quoted for post-operative instability/dislocation following primary THR. The impact of bearing surfaces, head sizes, and articulations used in primary THR were not investigated in this study. Evidence suggests that the surgical approach influences the risk of revision (175), the use of dual-mobility bearings reduces the incidence of dislocation following primary THR (176, 177, 178), larger head sizes increase stability (179, 180, 181), and the incidence of PJI is reduced when using ceramic on polyethylene articulations (182, 183, 184). However, as this study was performed using NJR data from a single institution, there is unlikely to be any significant difference in the use of surgical approach, bearing surface, head size, or articulation between consultants and trainees in primary THR.

3.5Conclusions

In conclusion, this study has highlighted the importance of appropriate consultant supervision during primary THR performed by surgical trainees which may, in conjunction with other reported risk factors, reduce the incidence of potentially avoidable early revision operations. (185, 186) This finding has implications for training boards, trainees, trainers, and healthcare institutions. Careful patient and implant selection and meticulous attention to anti-sepsis may help mitigate the recent trend observed in early revision procedures following primary THR. The NJR and its Research Committee should consider repeating this temporal group study with its entire national dataset to see if the same findings are observed. This is important as the findings of this study have important implications for consultant surgeons who have a recognized role in education and training, particularly in relation to how thresholds are set for determining outlier status and the acceptable incidence of revision procedures following primary THR. It is notable that the significant increased incidence of early revision operations following primary THR performed by unsupervised trainees in comparison to supervised trainees or consultants is also a recent phenomenon, which has only been observed in operations performed between 2015-2020. This finding may indicate that contemporary orthopaedic training programmes are failing to adequately prepare senior trainees to perform primary THR independently in comparison to their predecessors. Future research should focus upon optimising training methods and evaluating their impact on the technical skills performance of surgical trainees. The end goal of surgical training is to equip surgeons with the requisite knowledge, technical skills, experience, and judgement required to deliver safe and high-quality patient care, whilst optimising outcomes and reducing the incidence of potentially avoidable complications. To develop a focussed training module in primary THR it is important to firstly define the key steps of this operation, and subsequently determine which of these steps are particularly difficult to teach or are critical to patient outcomes. These questions are investigated in chapter four.

4 Expert consensus on the key performance and training parameters in primary elective total hip replacement.

This study has been published in HIP International in November 2021. (174)

4.1 Introduction

Despite its prevalence and importance, there are no agreed teaching methods for THR overall, or for any of its key stages. Furthermore, it is unknown if surgeons agree or disagree about the key stages and how best to teach them. To develop focused and effective surgical training it is critical to firstly define the key steps of the procedure. Defining and categorising these key steps in order of importance can be a challenge as there is a natural variation across surgeons who perform the same operation. Besides the surgeon's technical ability to perform each of these steps, it is also important to consider their ability to teach each step. An individual step may be judged by a trainer both according to how critical it is to patient outcome, and how easy it is to teach. Obtaining a balanced perspective from a large cross section of experienced surgeons who are actively involved in contemporary training offers the opportunity to improve surgical training in THR. Such consensus group methodologies are defined as a systematic means to assess, develop, and define levels of agreement between individuals. (187) The Delphi technique is now a recognised form of consensus methodology used in formulating an opinion within a group of experts in their domain of expertise (188).

4.1.1 The Delphi technique

Consensus group methodologies are defined as a systematic means to assess, develop, and define levels of agreement between individuals. (187, 189, 190) The Delphi technique is a recognised form of consensus methodology used in formulating an opinion within a group of experts in their domain of expertise on a research question where exact evidence is lacking. (188) The three original principles of the Delphi technique as described by Dalkey *et al* include: participant anonymity;

controlled feedback; and statistical analysis of the group response. (191) In addition to these principles, it is important to define the expert participants, and set a target number for recruitment. Although there is no exact consensus regarding the number of experts required for the Delphi technique, the size of the panel should reflect the availability of study resources, and the likelihood that the process produces a sound answer which is likely to be accepted. Delbecq *et al* have recommended that ten to fifteen participants could be sufficient if the background of the subjects is homogenous. (192) The target number of participants in round two of this study was set at 30 in order to maximise the reliability of the results generated (193). Multiple iterations of questionnaires are required (with a specified minimum of two), with structured and anonymised feedback between rounds. This controlled feedback allows participants to review the collated results from the group after each round, which may influence their opinion and responses to questions in subsequent rounds. All participants are therefore free to change their individual responses between rounds to questions where a consensus has not been achieved.

4.1.2 Aims

The aim of this study was to define the key steps of a primary THR, rank them in order of importance for patient outcome, and on ease of teaching to surgical trainees. The results generated may inform orthopaedic trainers, trainees, and training standard committees about the areas of THR training viewed as either critical to patient outcome or difficult to teach and that would benefit from particular focus or further strategies to enhance training.

4.2 Methods

4.2.1 Study and questionnaire design

Considerable variability and quality have been demonstrated in the application, structure, execution, and reporting of consensus methodologies in the healthcare setting. (189, 193) In this study a pre-determined maximum of three rounds was set for achieving group consensus, including the literature review and pilot survey. The first round generated a list of key steps of a primary THR using information from published orthopaedic journals and textbooks, and canvassing opinion using a pilot survey from a group of expert hip surgeons at the Nuffield Orthopaedic Centre in Oxford, which is a specialist tertiary orthopaedic hospital. This survey contained a provisional list of discrete steps involved in primary THR, open-ended questions, and space for free-text responses to gather and refine the final list of steps. The steps identified were sub-divided into *outcome* and *training* parameters to reflect the impact of each step on the outcome of the operation, and whether surgeons find it easy to teach the step to surgical trainees. The *outcome* parameter was assessed using a 3-point Likert scale, and the *training* parameter was assessed using a binary 'yes/no' answer. These scales were specifically selected to reduce any ambiguity in response and remove any requirement for 'grouping' responses which may be caused by increasing the number of response categories. (194) In round two, questionnaires were circulated to attendees throughout the 2019 British Hip Society Annual Scientific Meeting (Appendix A). This meeting was selected for distribution of the questionnaire as it is the national conference for orthopaedic hip surgeons with a sub-specialty interest in hip surgery and therefore attracts a high concentration of eligible participants. The eligibility criteria for participation in this study were clearly defined on the questionnaire as any consultant orthopaedic hip surgeon with an active or recent (within 5 years) role in surgical training. All completed questionnaires from surgeons not meeting the eligibility criteria were removed prior to analysis. Information on participant demographics and clinical profiles were collected. Following an interval of three months, a third round was conducted remotely via e-mail to all round two participants. All steps that achieved group consensus in round two were removed prior to distributing the revised questionnaire in round three. The electronic questionnaires used in round three were

constructed using a template on the online platform google forms (Google Forms; Google LLC, Mountain View CA). A series of three reminder notifications were sent at fortnightly intervals to all participants who did not complete the questionnaires. Responses from round three were closed at eight weeks following the initial contact, and all participants who had not responded by this time point were excluded from further involvement, however their responses from round two were included in the data analysis.

4.2.2 Data analysis

A unified definition of consensus when performing a Delphi analysis does not exist in the literature. (195) The benchmark for 'group consensus' in this study was set high at 80% agreement in any one category on the 3-point Likert or binary scale for each THR step, which is in keeping with the recommendations of many authors. (196, 197) The inter-rater reliability (IRR) is a statistical method of defining the amount of agreement between two or more raters who follow the same procedure. (35) The IRR ranges from 1 (perfect agreement), to -1 (perfect disagreement). (143) The criteria outlined by Koo and Li are used in this study, who recommend that values <0.5 indicate poor reliability, 0.5 to 0.75 indicate fair reliability, 0.75 to 0.9 indicate good reliability, and >0.9 indicates excellent reliability. (144, 145, 146) The inter-rater reliability (IRR) in rounds two and three are reported using a two-way random effect, consistency, average-measures intra-class correlation coefficient (ICC) with a 95% confidence interval to assess the reliability of participants ratings of the parameters for each step. (143, 198) The intra-rater stability of responses between round two and three for all parameters which do not meet group consensus are reported using a two-way mixed effect, absolute agreement, single-measures ICC with a 95% confidence interval. The significance threshold was set at 0.05 for all statistical analysis. Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA).

4.3 Results

4.3.1 Round One

A list of 26 discrete steps in performing a primary THR was generated using the findings from the literature review and pilot survey. These were used to construct a data capture questionnaire for distribution to eligible participants in round two (Table 4-1).

Table 4-1: Questionnaire distributed to participants in round two.

	How much impact do you feel the following steps have on the ***outcome*** of the operation? (Please tick **one** option)				Whether you find it easy ***to teach*** this step to your trainees? (Please tick **one** option)	
	Little	**Moderate**	**Substantial**		**Yes**	**No**
Pre-op Templating						
Patient Positioning						
Skin preparation and draping						
Skin Incision & Surgical Approach						
Acetabular Preparation						
Acetabular Exposure						
Labral resection/Osteophytectomy						
Acetabular Reaming						
Implant Sizing & Trialling (including trimming of cemented cup if using)						
Acetabular Component Implantation						
Anteversion						
Inclination						
Depth (e.g. medialising to floor)						
Femoral Preparation						
Femoral Exposure						
Femoral neck osteotomy						
Femoral canal preparation/broaching						
Implant Sizing & Trialling						
Femoral Component Implantation						
Version						
Varus/Valgus alignment						
Cementing (if applicable)						
Cement mixing & handling						
Acetabular drill holes						
Acetabular lavage & packing						
Acetabular cement insertion & pressurisation						
Femoral canal cement restrictor sizing						
Femoral canal lavage, suction & packing						
Femoral cement insertion & pressurisation						
Intra-Operative Assessment & Restoration of Hip Anatomy						
Assessing & accurately reconstructing Leg length						
Assessing & accurately reconstructing Hip offset						

4.3.2 Round Two

50 consultant hip surgeons across England and Scotland provided complete responses to the questionnaire in round two. Of these participants, 14 reported fewer than 5 years of experience as a consultant, 13 had between 5 to 10 years' experience, 5 had between 10 to 15 years' experience, 11 had between 15 to 20 years' experience, and 7 had greater than 20 years' experience. Overall, 17 participants worked within a university teaching hospital (UTH), and 33 worked within district general hospitals (DGH). The participants worked in hospitals across a wide geographical area within the UK (figure 4-1). 48 were actively involved in training orthopaedic specialty registrars or fellows, and all participants had trained surgeons within the last five years. 42 were currently clinical supervisors of specialty registrars or fellows. Digital pre-operative templating was routinely used by 41 participants (82%), in comparison to 6 who manually templated (12%), and 3 who did not routinely template (6%). A lateral decubitus patient position was used by 46 participants (92%), with 4 reporting the use of a supine position (8%). A posterior surgical approach was routinely used by 43 participants (86%), with 6 reporting the use of a Hardinge (direct lateral) approach (12%), and 1 using a direct anterior approach (2%). Hybrid implant fixation (uncemented acetabular cup with cemented femoral stem) was preferred by 23 participants (46%), followed by all cemented implants by 15 participants (30%), all uncemented implants by 5 participants (10%), a mixture of implant fixation modes by 4 participants (8%), and reverse hybrid fixation by 3 participants (6%). The clinical profiles and surgical preferences of round two participants are summarised in table 4-2.

Figure 4-1: Geographical distribution of expert participants in round two.



Table 4-2: Clinical profiles and surgical preferences of Delphi round two participants.

Clinical profiles of round 2 participants	N = 50[1]
Hospital setting	
University Teaching Hospital	17 (34%)
District General Hospital	33 (66%)
Consultant experience	
<5 years	14 (28%)
5-10 years	13 (26%)
10-15 years	5 (10%)
15-20 years	11 (22%)
>20 years	7 (14%)
Current surgical trainer	
-Yes	48 (96%)
-No	2 (4.0%)
Trained surgeons within 5 years	
-Yes	50 (100%)
Academic or clinical supervisor	
-Yes	42 (84%)
-No	8 (16%)

[1] n (%)

Surgical preferences of round 2 participants	N = 50[1]
Templating	
Digital	41 (82%)
Manual	6 (12%)
None	3 (6.0%)
Patient positioning	
Lateral decubitus	46 (92%)
Supine	4 (8.0%)
Surgical approach	
Posterior	43 (86%)
Hardinge	6 (12%)
Anterior	1 (2.0%)
Implant fixation	
Hybrid	23 (46%)
Cemented	15 (30%)
Uncemented	5 (10%)
Reverse Hybrid	3 (6.0%)
Combination	4 (8.0%)

[1] n (%)

Data on the operative profiles for primary and revision THR of each participant were obtained from the publicly available section of the United Kingdom's National Joint Registry (NJR) website (https://surgeonprofile.njrcentre.org.uk/). Data were not available for a total of 5 participants. Of the remaining 45 participants, the mean number of primary and revision THR performed was 372 and 51 over 36 months. The 12 and 36 months NJR profiles of round two participants is summarised in figure 4-2. The scatterplots have been faceted according to the participants hospital setting (vertical facets), and dotted lines added to indicate the national mean average operative numbers for primary and revision THR according to the NJR. (199) Pearson product moment correlation coefficient (PPMCC), p-values, and linear regression lines with 95% confidence intervals are also shown on the scatterplots. Significant positive correlations were identified between the number of primary and revision THR performed by participants over a 12- and 36-month period within both a UTH and DGH setting.

Consensus agreement was achieved in 27 of 52 parameters assessed: 12 for importance on patient outcome, and 15 for ease of teaching. The following steps achieved greater than 90% consensus for their substantial impact on patient outcome following primary THR: skin incision and surgical approach, acetabular reaming, reconstructing leg length, acetabular cup version, femoral stem version, and femoral cement insertion. Overall, 40% or more of participants rated the following steps as not easy to teach to surgical trainees: acetabular reaming, acetabular cup version, reconstructing hip offset and leg length. The collective responses from all 50 participants in round 2 are summarised in the stacked bar plots in figures 4-3 and 4-4. A vertical dotted line has been marked on each bar plot to indicate the 80% threshold required for achieving group consensus.

The inter-rater reliability across all participants was 0.89 (CI 0.8-0.94) for the impact on outcome parameters, and 0.82 (CI 0.73-0.89) for the ease of teaching parameters. A total of 3 participants recorded non-applicable responses to the steps on acetabular cementing, as they did not use this technique in their practice. Following review of the free text responses, 1 further step (soft tissue handling and wound closure) was added for assessment in round three.

Figure 4-2: Scatterplots demonstrating the summary 12 and 36 months NJR profiles of round two participants for primary and revision THR.

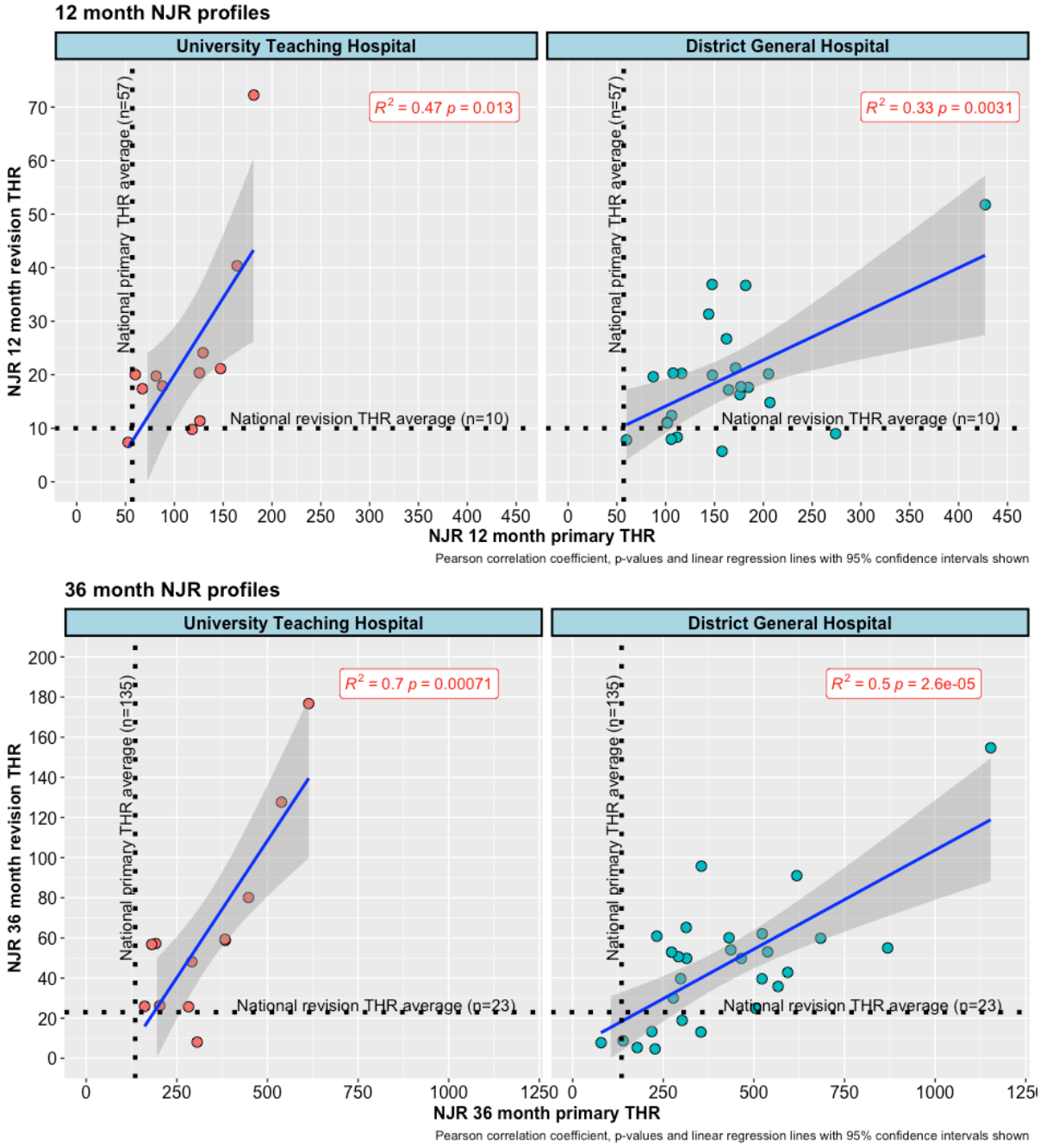


Figure 4-3: Stacked bar plot of participant ratings in round two for the impact of each step on the outcome of the operation.

Dashed line indicates 80% consensus threshold

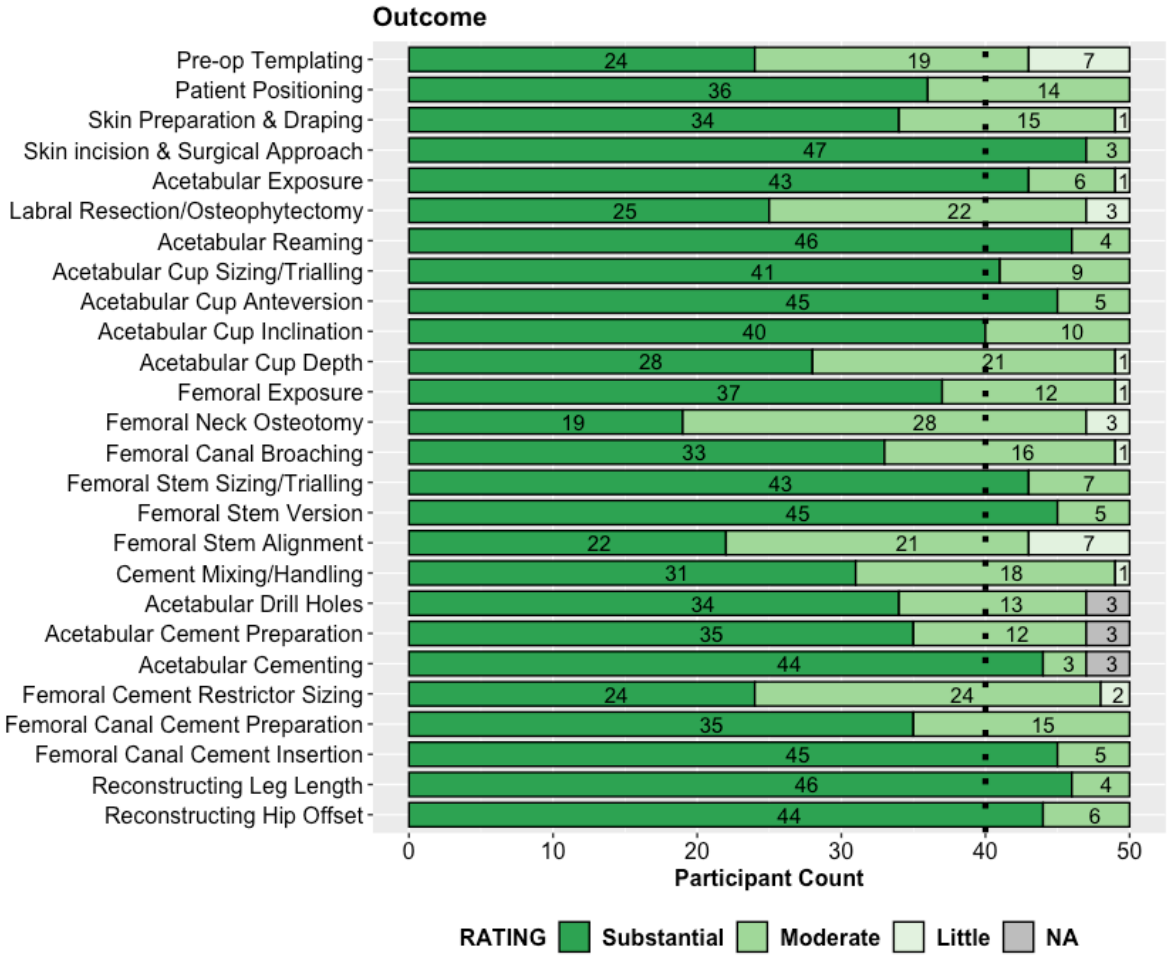
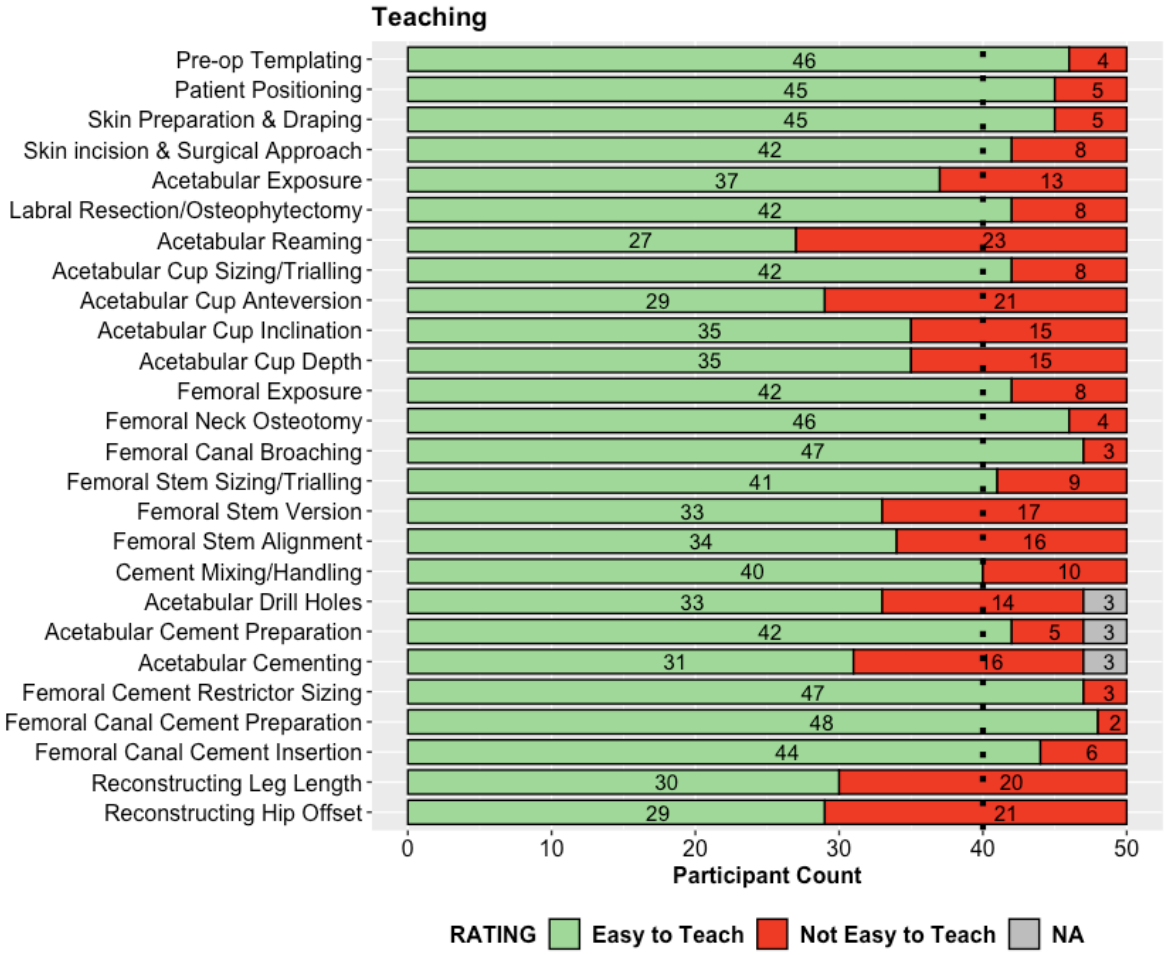


Figure 4-4: Stacked bar plot of participant ratings in round two for the ease of teaching each step of the operation.

Dashed line indicates 80% consensus threshold



4.3.3 Round Three

A total of 27 parameters were assessed in the questionnaire in round three: 15 for importance on outcome, and 12 for ease of teaching. 25 parameters were from round two, where consensus had not been achieved, and a further 2 from the additional step of soft tissue handling and wound closure. Complete responses were received from 28 participants in round three, and consensus agreement was achieved in a further 6 parameters. The 4 parameters achieving consensus for importance on outcome were: patient positioning, soft tissue handling and wound closure, skin preparation and draping, and cement mixing and handling. The 2 parameters achieving consensus for ease of teaching were: acetabular drill holes, and soft tissue handling and wound closure. The collective responses from all 28 participants in round three are summarised in the stacked bar plots in figures 4-5 and 4-6. A vertical dotted line has been marked on each bar plot to indicate the 80% threshold required for achieving group consensus. The inter-rater reliability across all participants was 0.92 (CI 0.86-0.96) for the impact on outcome parameters, and 0.73 (CI 0.73-0.89) for the ease of teaching parameters. Following round 3, a total of 21 parameters remained without group consensus: 11 for impact on patient outcome, and 10 for ease of teaching.

4.3.4 Change in response between round 2 and 3 for parameters not achieving consensus

Between rounds 2 and 3 participant responses changed less than 25% for 3 parameters; less than 50% for 16 parameters; and greater than 50% for 2 parameters. The 3 parameters for which participants responses changed less than 25% were: the impact of pre-operative templating on patient outcome, and the ease of teaching both acetabular cup inclination and acetabular reaming. The 2 parameters for which participants responses changed greater than 50% were: the impact of femoral cement restrictor sizing, and femoral stem alignment on patient outcome.

Overall, 16 parameters achieved an 80% consensus agreement for their impact on the outcome of the operation, and 17 for ease of teaching. The rank order of parameters achieving consensus for importance on outcome of the operation, alongside the parameters which did not achieve consensus for ease of teaching (therefore perceived as difficult to teach) were of primary interest. The participants ratings for these steps are summarised in the stacked bar plots in figures 4-7 and 4-8, which are arranged in rank order of agreement. A vertical dotted line has been marked on each bar plot to indicate the 80% threshold required for achieving group consensus.

Figure 4-5: Stacked bar plot of participant ratings in round three for the impact of each step on the outcome of the operation.

Dashed line indicates 80% consensus threshold.

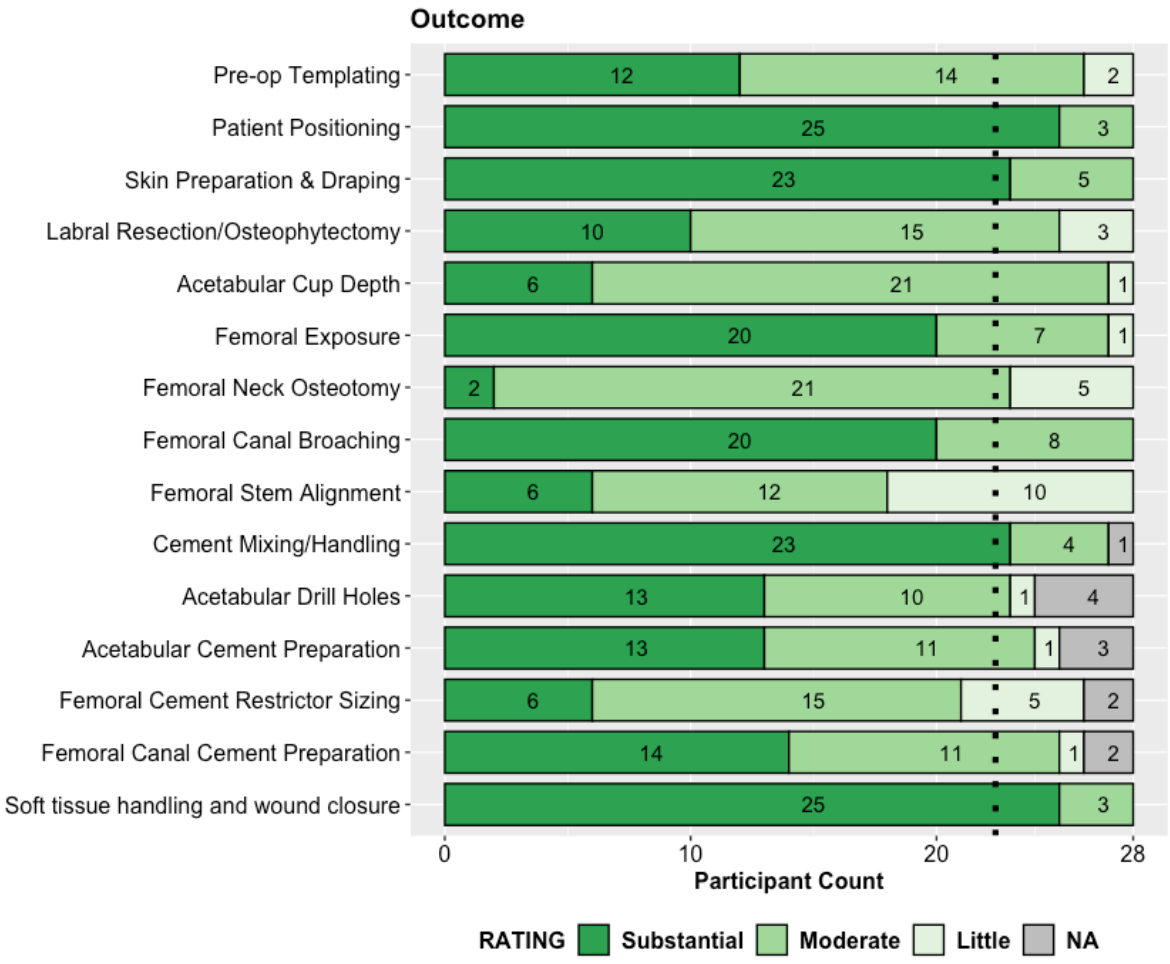


Figure 4-6: Stacked bar plot of participant ratings in round three for the ease of teaching each step of the operation.

Dashed line indicates 80% consensus threshold.

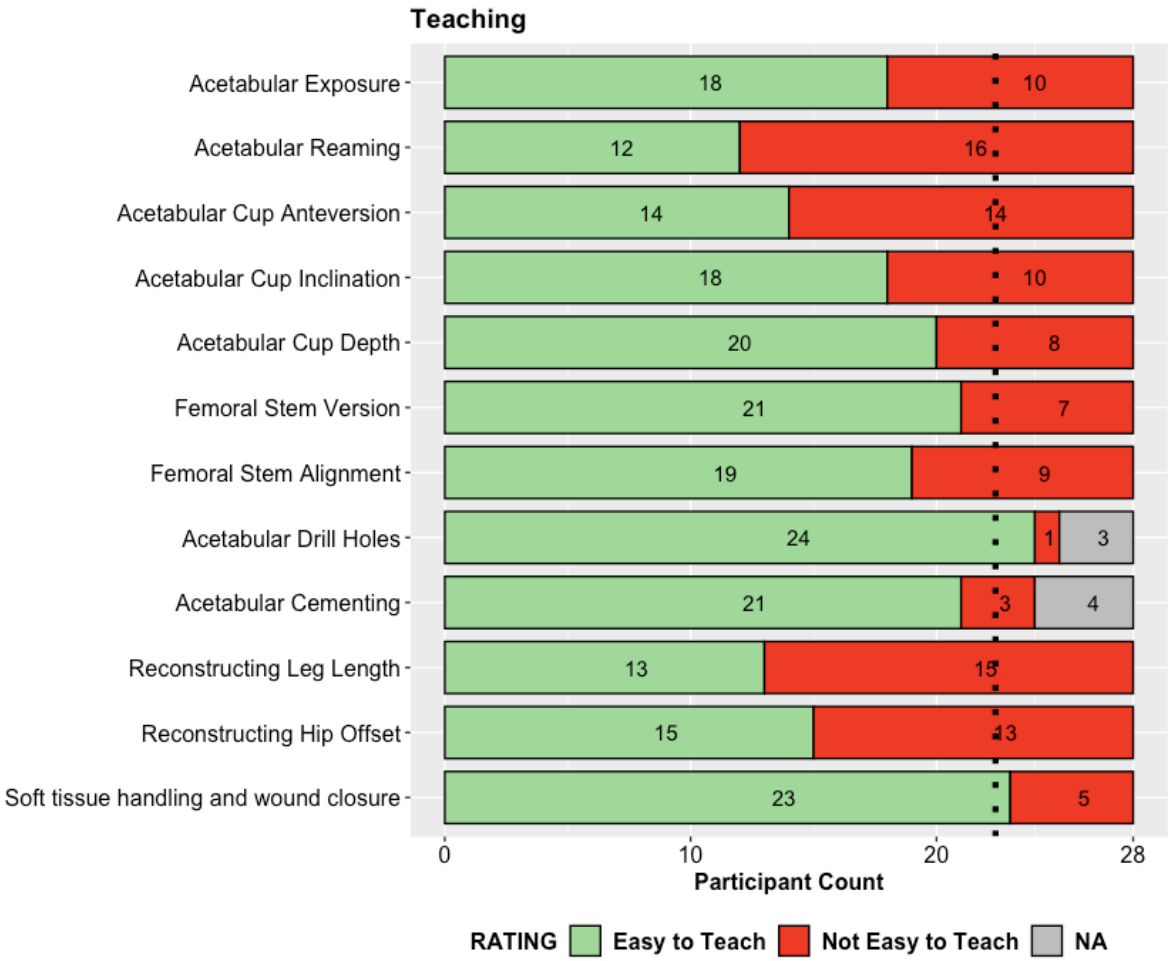


Figure 4-7: Stacked bar plot showing the rank-order of steps achieving consensus for importance on the outcome of the operation.

Dashed line indicates 80% consensus threshold.

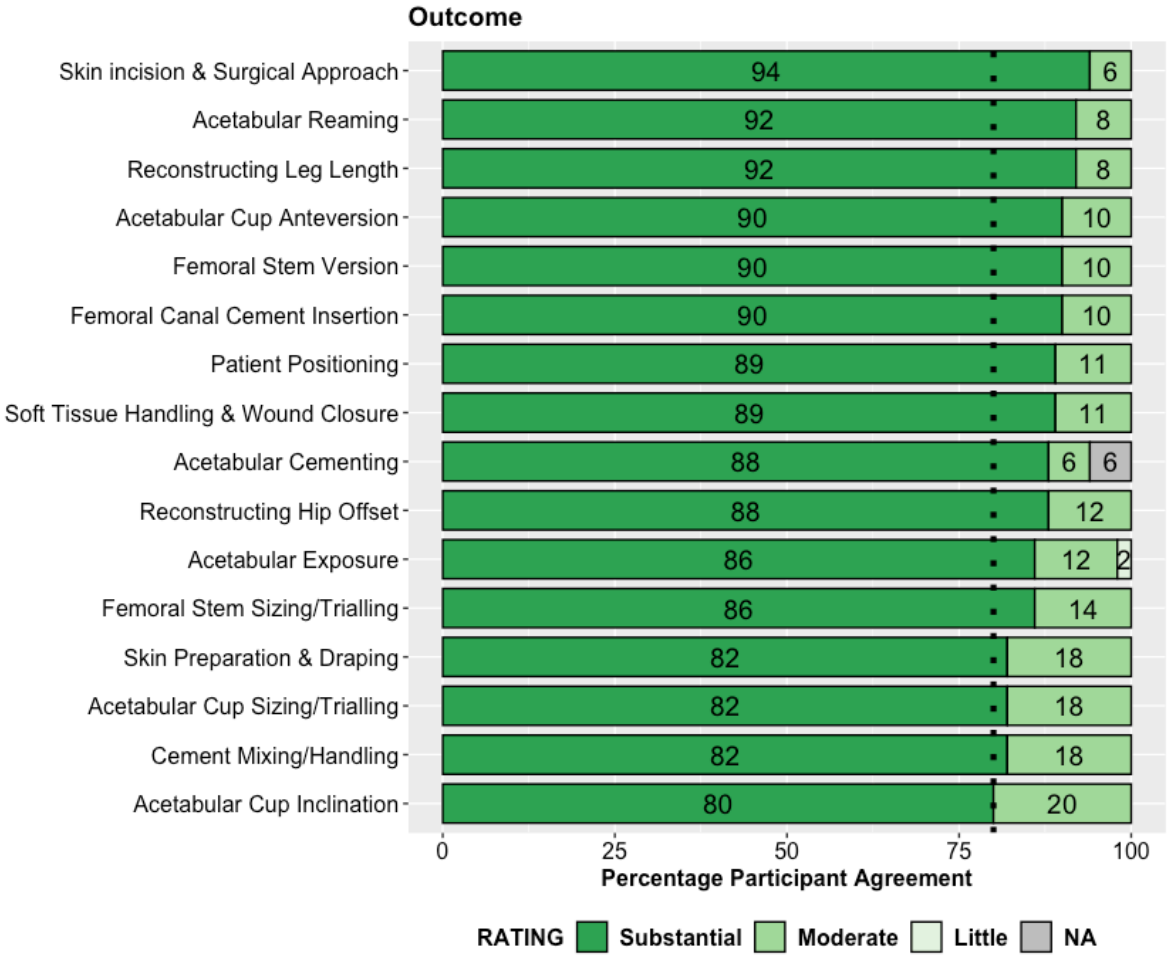
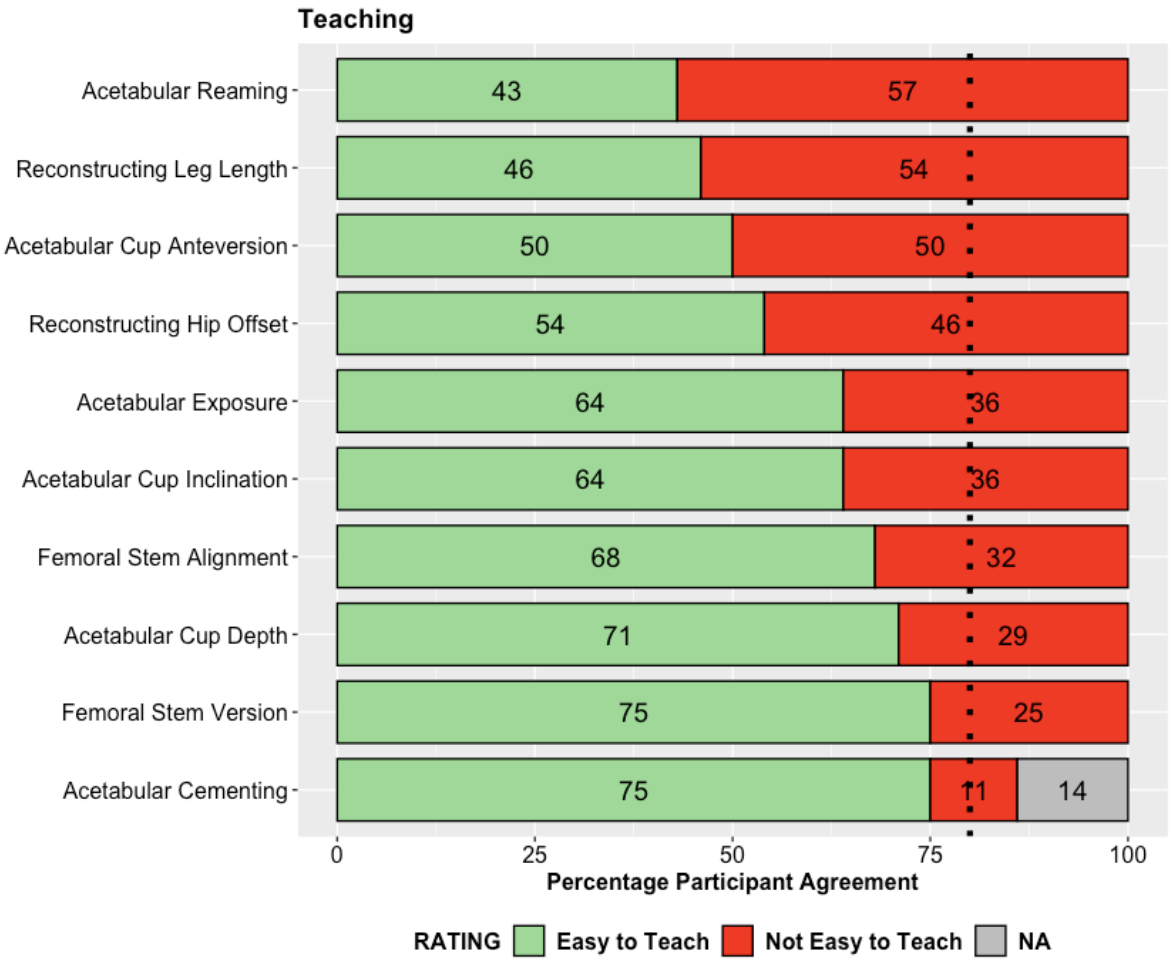


Figure 4-8: Stacked bar plot showing the rank-order of steps not achieving consensus for ease of teaching surgical trainees.

Dashed line indicates 80% consensus threshold.



A total of 8 steps reached consensus for both importance on their impact on the outcome of the operation and did not achieve consensus for ease of teaching (table)

Table 4-3: Summary table of steps which achieved group consensus for their significant importance on the outcome of the operation, and not for ease of teaching.

Step	% Rated as having a substantial impact on the outcome of the operation (rank order)	% Rated not easy to teach (Rank order)
Acetabular reaming	92% (2)	57% (1)
Assessing & accurately reconstructing leg length	92% (2)	54% (2)
Acetabular cup anteversion	90% (3)	50% (3)
Assessing & accurately reconstructing hip offset	88% (5)	46% (4)
Acetabular exposure	86% (6)	36% (5)
Acetabular cup inclination	80% (8)	36% (5)
Femoral stem version	90% (3)	25% (9)
Acetabular cement insertion & pressurisation	88% (5)	11% (10)

4.4 Discussion

4.4.1 Summary and relevance of findings

Several steps identified within this study are recognised as having a substantial impact on patient outcome following primary THR, most notably: pre-operative templating (200), patient positioning (201), surgical approach (202), acetabular cup and femoral stem positioning (117, 203, 204), restoration of femoral offset (100, 205), balancing leg lengths (204), and wound closure (206). What this study adds to the scientific literature is an agreed rank-order list of the key steps involved in primary THR to achieve the best patient outcomes, as well as defining the steps that are difficult to teach surgical trainees. Differences between surgical trainees and experienced orthopaedic surgeons have been noted in relation to operative timings, patient complications, revision rates, and outcomes following primary THR. (25, 26, 27, 30) However, specific areas for improvement in training to overcome these differences have not been identified or recommended. There is a need to develop novel methods for improving training and performance in primary THR, and the results of this expert consensus form the first step in this process. Participant identification and selection are critical components of the Delphi technique, as the quality of participants dictates the results generated. No specific criteria exist to define an expert in hip surgery however, experts should generally be well-regarded representatives of their profession; highly trained, knowledgeable, and competent within the specialised area related to the target issue; and have the ability to implement the findings of the study. (188) The strengths of this study include attention to the clinical profiles of the expert participants, notably the geographical spread, hospital setting, years of experience, and operative numbers which are representative of the wider orthopaedic community. The ratings of these participants therefore provide a good insight into and reflection of contemporary surgical practice and training. According to NJR figures, the mean 36-month primary and revision THR procedures performed by participants within our study was considerably higher than the national average, indicating that these participants are representative of a high-volume group of surgeons with the concomitant increase in experience and may therefore be justly regarded as experts. Using this relatively large demographic of expert participants in combination with adherence to the pre-

determined and robust Delphi technique methodological criteria and using a high threshold for defining consensus adds validity to the findings. While this study identifies consensus for 33 out of 54 parameters, a total of 21 parameters remained without group consensus. The 10 parameters which did not achieve consensus for ease of teaching are of particular interest as they constitute the steps which surgeons perceive as difficult to teach trainees. A simulation-based approach to training surgical trainees in these steps in a non-clinical environment may therefore be beneficial prior to refining their skills under supervision in clinical practice. All 16 parameters achieving consensus for impact on the outcome of the operation were rated in the substantial category on a 3-point Likert scale (figure 4-7). It is important to highlight that the 11 parameters which did not achieve consensus for impact on the outcome of the operation remain important steps of a THR. The fact that consensus was not achieved may reflect our high threshold, or that participants ratings on the degree of their individual impact (substantial/moderate/little) were more evenly distributed for these steps. A total of 9 out of 11 parameters which did not achieve consensus for impact on the outcome of the operation had kappa values of less than 0.5, indicating poor intra-rater reliability. This reflects the change in participants ratings for these parameters between rounds of the study. Conducting further iterative rounds of the Delphi process may theoretically increase intra-rater reliability, however, we believe that the risk of participant fatigue, increased drop-out rates, and diminishing returns outweighed this potential benefit. The results of this study may be particularly useful in guiding focused interventions for optimising orthopaedic surgical training in primary THR, ultimately aimed at reducing complications and adverse patient outcomes. These results may be used in the subsequent chapter to develop a new simulation-based training course for orthopaedic trainees, which focuses on the highly ranked critical steps of a primary THR. Orthopaedic surgeons who are actively involved in teaching and training along with their trainees can use the findings of this study as a framework to identify specific areas for personal development. Similarly, local hospitals, regional networks, and even national organisations responsible for developing curricula and delivering post-graduate medical education may decide to enhance both simulation-based and clinical training opportunities in the steps identified as critical to the outcome or perceived as difficult to teach ‘on the job’.

4.4.2 Limitations of study

One limitation of the Delphi technique is that it does not allow participants to discuss, debate, or elaborate their views on the issues raised within the questionnaire. However, the free-text responses within round 2 allowed participants to raise their ideas regarding amendments or further steps to be added within the questionnaire, which in this study resulted in an additional step being included in round 3. Another potential weakness relates to the preferred implant fixation used by surgeons. Comparison of the participants' implant fixation preferences to the NJR data suggest that users of hybrid fixation were over-represented, and so users of all uncemented implants were potentially under-represented within this study. A participant's choice of implant fixation may affect their individual attitudes and subsequently their ratings of the importance of specific steps of this operation. For example, surgeons who routinely use uncemented femoral stems may place a greater emphasis on the femoral neck osteotomy as this largely dictates leg length on the femoral side. Furthermore, 3 surgeons did not respond to the steps involving cemented acetabular cups as this was not applicable to their practice. Such limitations are a consequence of using a pragmatic questionnaire which was aimed at capturing and assessing the breadth of orthopaedic practice and implant combinations.

4.5 Conclusions

This expert consensus on the key performance and training parameters in primary total hip replacement has produced a rank-order list of steps which may be used by organisations, trainers and trainees in both curriculum development and enhancing surgical training opportunities specific to the aspects of this operation and viewed as important to patient outcomes and/or difficult to teach. The findings of this study are used in the next chapter as a foundation to guide the development of a focussed simulation-based training module for orthopaedic surgical trainees in primary THR. The purpose of this training module is to streamline surgical training in primary THR, optimise surgeon performance, and further improve outcomes for future THR patients.

5. Developing a simulation-based training module for primary elective total hip replacement.

5.1 Introduction

Despite its prevalence and importance, there are currently no standardised training methods for THR. Training standards and guidelines for the achievement of competence in THR have been outlined by the JCST. To be deemed competent in the technical procedural skills of THR, current JCST guidelines (2017/18 update) for CCT in trauma & orthopaedic surgery stipulate that trainees provide evidence of at least 80 major joint (hip, knee, shoulder, or ankle) arthroplasty cases performed as first surgeon, and a total of three level 4 PBAs by at least two independent assessors. (17) These target-driven guidelines do not provide any guidance on recommended strategies to best achieve these competences, and no formal written advice has been published regarding training in THR by any of the advisory, regulatory, or professional bodies. Recognised restrictions in contemporary surgical training programmes have reduced both the volume and breadth of in-training surgical experience. Such restrictions include but are not limited to reduced working times (European Working Time Directive); increasing patient expectations and consultant-led care; and increasing pressure from management for theatre efficiency and service provision. Given these restrictions, there is a need for a focused, evidence-based, and unified approach to surgical training to maximise opportunities for trainees to achieve operative competence prior to CCT. The rationale for developing the training module outlined in this chapter is to deliver the core scientific knowledge and theory underpinning a successful primary THR, allow trainees the opportunity to practise key steps of this operation in the safety of a simulated environment, and use validated assessment tools to assess trainee's performance in both the theoretical and practical technical procedural skills required in the critical steps of this operation as outlined in chapter 4. The impact of this focused and evidence-based module on the knowledge and operative technical skills performance of trainees is investigated in subsequent study chapters 7 and 8.

5.2 Task selection, content, and structure of training module

5.2.1 Aims

Develop a structured training module involving simulation techniques in primary THR for orthopaedic surgical trainees.

5.2.2 Methods

Results from the expert consensus outlined in chapter 4 were used to guide the content and structure of this training module. (174) The module is particularly focussed on the steps deemed both critical to patient outcomes and particularly difficult to teach 'on the job'. The educational content is delivered using three formats:

- Taught didactic lectures
- Simulated practical skills
- Delegate workbook

The core scientific knowledge and theoretical elements are contained within the didactic lectures and delegate workbooks. The practical skills sessions use a range of simulation models and equipment designed to allow delegates hands on experience with the surgical instruments and techniques commonly used in primary THR under the direct supervision of experienced faculty and in the safety of a non-clinical environment. Formative cognitive and practical skills assessments with verbal feedback is undertaken before, during, and after the module to highlight and reenforce areas for personal improvement. A detailed description of these assessment tools, including the methodology used to validate them, is outlined in studies 5.3 and 5.4. Optional written feedback was requested from all delegates attending the module to enhance the content, structure, and overall experience of trainees in future iterations of this module.

5.2.2.1 Core content and structure of the training module

To maximise the learning opportunities within a short time frame, this training module was delivered in a single day rather than spread over several sessions. Limitations in human and physical resources (including the availability of faculty, seminar room, and simulation models) restricted attendance to a maximum of eight participants per day. In addition to the sections outlined below, an introductory lecture also provides information on the principles of THR including indications & contra-indications; hip biomechanics; implant fixation and the role of the National Joint Registry (NJR), and Orthopaedic Data Evaluation Panel (ODEP). The core education content of this training module is divided into four sections reflecting the sequential stages of a THR. Each section has been divided into sub-sections based upon the fundamental steps of a primary THR outlined in the expert consensus in chapter 4.

1) Principles of THR, templating, patient set-up & surgical approach

a. Templating in THR
b. Patient positioning & set-up
c. Skin preparation, draping, and antibiotic administration
d. Anatomy of the hip, skin incision, & surgical approach

2) Acetabular exposure, preparation, and component implantation

a. Techniques for optimising acetabular exposure: retractor positioning; soft-tissue releases; labral resection/osteophytectomy
b. Reaming
c. Uncemented cup trialling, sizing & positioning
d. Acetabular screw holes (uncemented cups)
e. Drill holes (cemented cups)
f. Cemented cup trialling, sizing & positioning
g. Cementing technique and cup implantation

3) **Femoral exposure, preparation, and component implantation**

   a. Femoral exposure

   b. Femoral neck osteotomy

   c. Femoral component selection

   d. Femoral canal preparation and implantation for cemented/uncemented stems

4) **Reconstructing hip biomechanics and closure**

   a. Centre of rotation (COR) of the hip joint

   b. Femoral offset (FO) and acetabular offset (AO)

   c. Femoral neck version and neck-shaft angle (NSA)

   d. Acetabular orientation (inclination and version)

   e. Leg length (LL)

   f. Surgical closure following THR

5.2.3 Results

5.2.3.1 Taught components

The taught components relating to each section of the training module were delivered using a series of four didactic lectures, with each lecture lasting no longer than one hour. These lectures were complemented with intra-operative videos and images of the key steps of a THR. The medical images used were recorded with appropriate, trust-approved written informed patient consent and did not contain any patient identifiable features.

Figure 5-1: Set-up of seminar room used for delivering the didactic lectures during course.



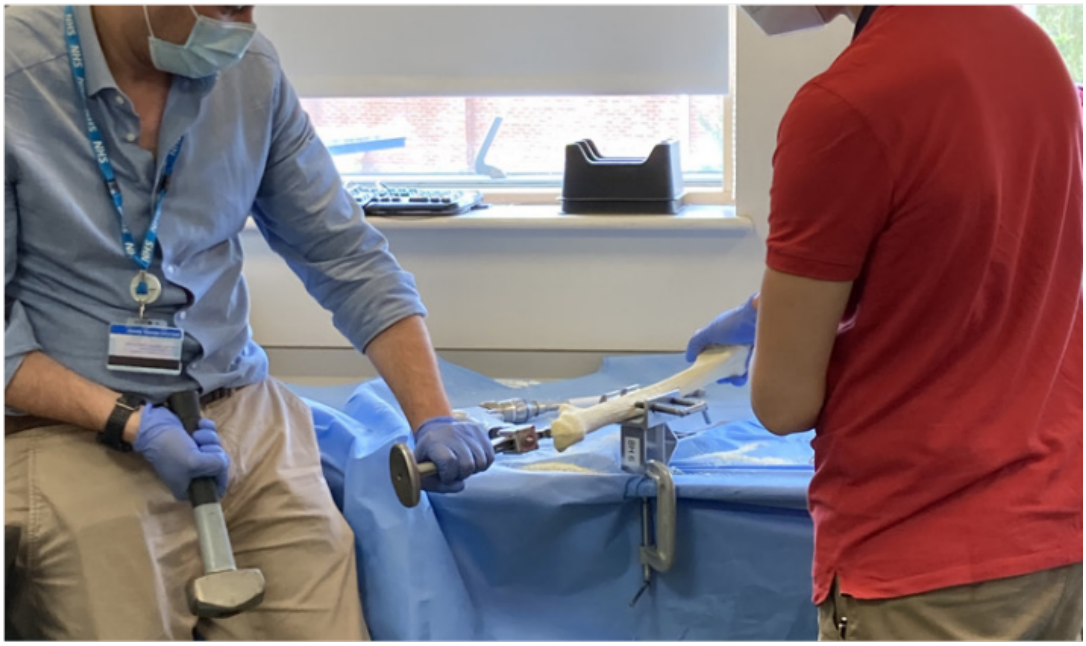
5.2.3.2 Simulated practical components

The participants were fully briefed on the expected learning outcomes prior to each simulated practical skills session. A range of physical simulators were used in the delivery of this training module. Factory made adult male pelvis, femur, and hip models were purchased from Sawbones® (Pacific Research Laboratories, Sawbones Europe AB, Limhamn, Sweden). Bespoke simulators were also developed which allowed participants to practise the psychomotor skills of both acetabular and femoral preparation and assess in real-time the orientation of component implantation. The development and validation of the bespoke simulator tools is discussed in sections 5.3 and 5.4. Acetabular and femoral preparation and component implantation (including cementing techniques) were chosen for simulated technical skills practice as the expert consensus highlighted these steps as some of the most critical in determining patient outcome following primary THR.

During the training module participants were individually given the opportunity to prepare and implant both acetabular and femoral components for uncemented and cemented prostheses using these synthetic simulation models under the supervision of experienced faculty. Procedure-specific surgical equipment in the form of instruments (Corin Group Ltd., The Corinium Centre, Cirencester, UK), prostheses (Stryker UK, Stryker House, Newbury, UK), and bone cement (Heraeus Noblelight Ltd, Newbury, UK) were provided gratis through corporate educational grants. The aim of using these bespoke models and equipment was to maximise the physical and functional fidelity of the simulated tasks, as visual, tactile, and verbal feedback are all important factors in technical skills acquisition. “Although surgeons may behave differently under simulated conditions, if the tasks are designed carefully to reflect real surgical practice such tests could fulfil the essential requirements of feasibility, reliability, and validity”. (18)

Figure 5-2: Participants taking part in simulation practical sessions.

Femoral broaching using synthetic bones



Acetabular reaming using synthetic bones

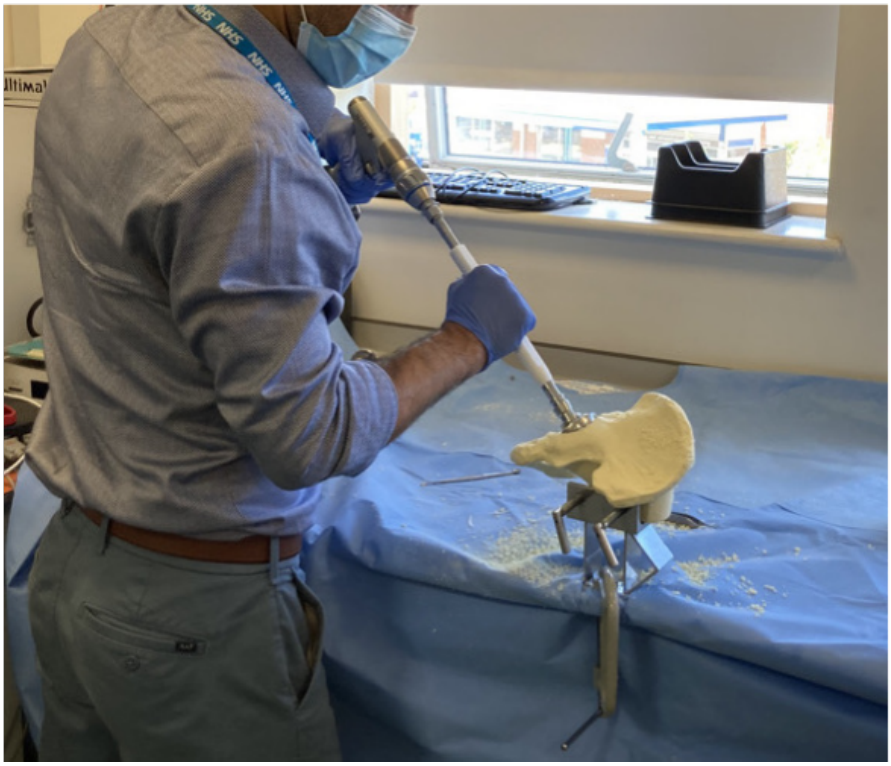
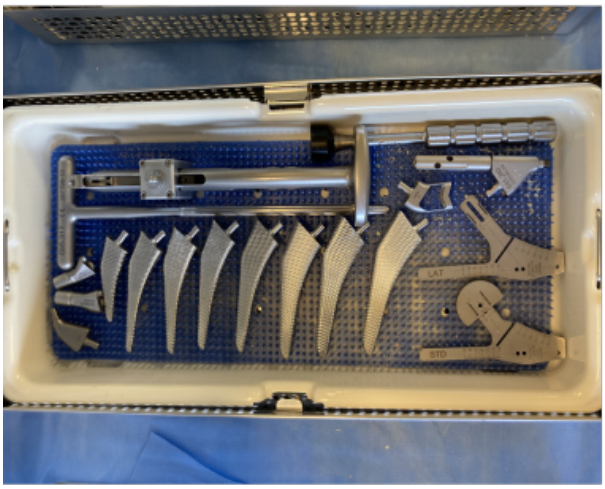
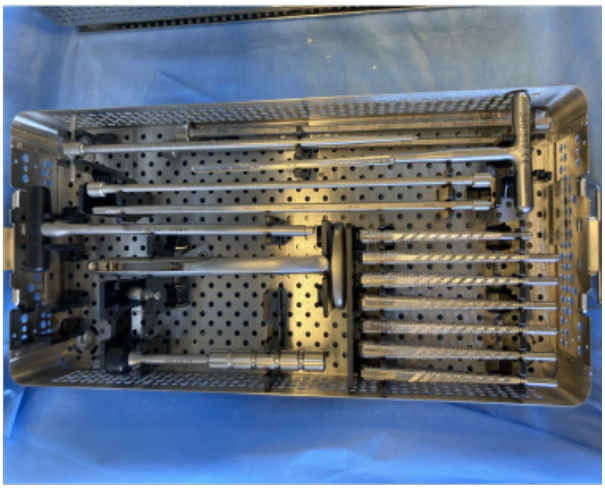


Figure 5-3: Surgical equipment used in simulation practical sessions.

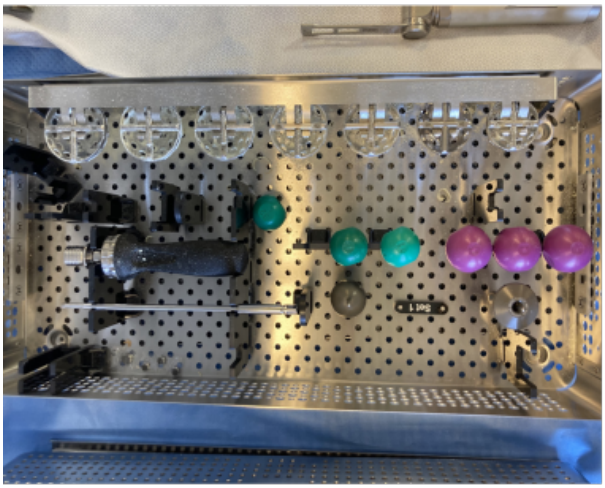
Uncemented femoral stem tray



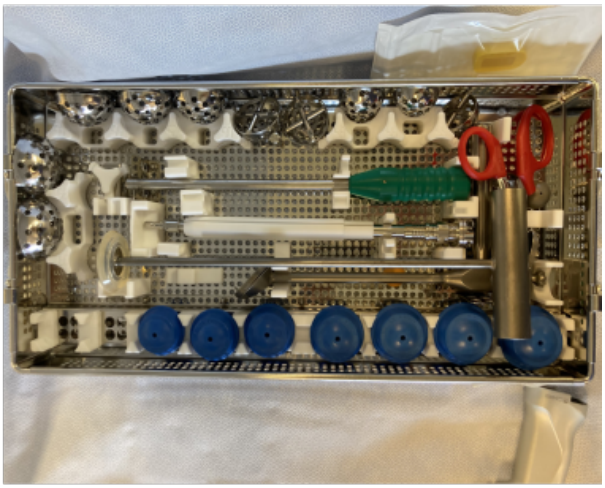
Cemented femoral stem tray



Uncemented acetabular cup tray



Cemented acetabular cup tray



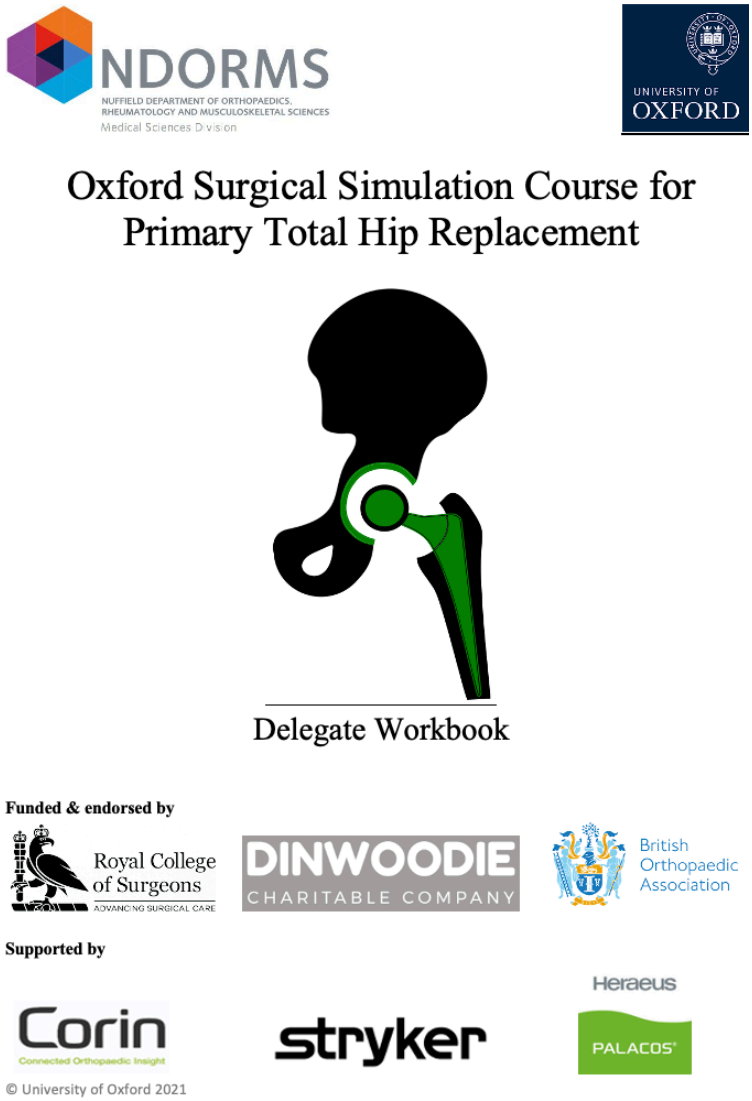
Power tools



5.2.3.3 Delegate workbook

The core educational content of the taught components of this module was also used to compile a complimentary delegate workbook, which was issued to all specialty registrars who attended the course (Appendix B.1). The content of this workbook reflects and re-enforces the concepts and techniques delivered in the taught and practical skills sessions. The production of this workbook was funded through charitable research grants and is intended to be used as a continuing reference for the trainees during their clinical placements.

Figure 5-4: Front page of delegate workbook for the Oxford surgical simulation course for primary total hip replacement.



5.3 Validation of assessment tools used within the training module

Four assessment tools were designed, developed, and validated for use in this training module to objectively evaluate participants knowledge and technical procedural skills in primary THR. The sequence and methodology for validating these tools has been outlined in the chronological order when performing a THR. The linked studies in this section focus upon assessing the participants background knowledge in the principles of THR using multiple-choice questionnaires, followed by assessing their practical skills in both pre-operative templating and surgical approaches in THR. The study in section 5.4 focusses upon validating a tool for assessing the participants intra-operative procedural skills in both acetabular cup and femoral stem implant orientation in simulated THR.

5.3.1 Aims

To develop and validate tools for assessing participants knowledge on the principles of THR, and skills in pre-operative templating and commonly used surgical approaches in THR.

5.3.2 Multiple choice questionnaire

In the field of medical education, multiple- and extended- choice questionnaires (MCQs and EMQs, respectively) are a well-established method for examining an individual's knowledge. Summative written MCQs and EMQs form part of the Joint Committee on Intercollegiate Examinations (JCIE) Fellowship examinations in Trauma & Orthopaedic Surgery. Well-structured standardised forms of these assessments have been shown to be both highly efficient, reliable, and able to assess higher-order thinking in candidates. (207, 208) When designing a novel educational assessment tool, the reliability and validity of that tool must first be established. (209) The outcome (result/score) of any assessment tool is determined by the standard-setting method used, (210) with the passing standard described as a "boundary between those who perform well enough and those who do not." (211) The two most used standard setting methodologies for written medical education examinations are the norm-reference and criterion-reference methods. (212, 213) Although there is no 'gold standard' method for determining a pass score the modified Angoff method is the most widely used criterion-

reference method of standard setting, which has been shown to have good inter-rater reliability and moderate test-retest reliability. (212, 213, 214, 215, 216) One major advantage of using this method of standard setting is that the passing score is determined by the content of the examination, and not the performance of the group being examined.

5.3.2.1 Methods

The modified Angoff method requires a panel of expert judges to review and individually rate each question stating the expected percentage of 'borderline' or 'minimally competent' candidates who would answer the question correctly. For the purposes of this research the borderline candidate is defined as 'an orthopaedic trainee who possesses the minimum level of knowledge and skills necessary to perform at a specialty registrar level'. The 'modified' aspect of the Angoff method removes any group debate regarding the cut-off percentages used for each question. The rating for each individual question should have agreement to within 30% between raters, and any outliers should be asked to justify their reasoning for extreme cut-off marks. The mean average score of the judges' ratings for each question is then calculated, and the pass mark for the exam is set as the mean average of the total scores for all questions. Two separate 20 question MCQs were constructed in this study for evaluation by expert judges, with the intention of administering one MCQ before and one after completion of the training module (Appendix B.2). The purpose of these MCQs was to establish a baseline cognitive performance in all participants and quantify any changes following completion of the training module. The difference in MCQ scores may be used as a surrogate marker to quantify the 'knowledge gain' following completion of the training module. The aim was to produce a set of validated, reliable, balanced, and fair MCQs which tested the participants critical scientific knowledge, theory and understanding of primary THR. All the MCQs were specifically constructed for this study and a group of three expert hip consultants rated each question. The experts were given clear instructions regarding the modified Angoff method, and the definition of a borderline candidate. They were also asked to provide feedback on the structure and content of each question, which were then edited and re-scored if necessary.

5.3.2.2 Results

No questions were completely removed following evaluation by the expert hip consultants. The judges' ratings for the pre- and post-course MCQs are outlined in table 5-1. No discrepancy in rating greater than 30% existed between experts in either MCQ. A a two-way random effect, average-measures intra-class correlation co-efficient (ICC) with a 95% confidence interval was used to assess the inter-rater agreement and reliability of the expert rating for the pre- and post-module MCQ. (143, 198) The ICC for the pre-module MCQ was 0.91, 95% CI [0.8-0.96], $p<0.001$, and for the post-module MCQ was 0.64, 95% CI [0.24-0.85], $p=0.0036$. These ICC values indicate excellent and fair inter-rater reliability for the pre- and post-module MCQs respectively. The total mean average of the individual means for questions in the pre- and post-module MCQs was 70.2% and 72.4%, respectively, which equates to a pass mark of 14 out of 20 for both MCQs.

Table 5-1: Judges ratings and ICC for the pre- and post-module MCQs.

Pre-module MCQ						Post-module MCQ				
Question	Rater 1	Rater 2	Rater 3	Mean average		Question	Rater 1	Rater 2	Rater 3	Mean average
1	70	70	50	63.3		1	80	80	70	76.7
2	60	75	70	68.3		2	70	90	80	80.0
3	70	70	70	70.0		3	70	80	70	73.3
4	40	5	40	28.3		4	70	80	70	73.3
5	30	50	50	43.3		5	80	80	80	80.0
6	40	60	50	50.0		6	70	80	60	70.0
7	90	90	90	90.0		7	80	70	60	70.0
8	70	70	60	66.7		8	70	70	40	60.0
9	60	70	80	70.0		9	80	90	80	83.3
10	30	50	60	46.7		10	90	90	90	90.0
11	80	90	90	86.7		11	80	90	90	86.7
12	80	90	90	86.7		12	80	60	90	76.7
13	80	90	90	86.7		13	80	70	90	80.0
14	80	80	90	83.3		14	60	75	70	68.3
15	70	80	90	80.0		15	70	40	60	56.7
16	60	80	70	70.0		16	70	75	60	68.3
17	80	90	80	83.3		17	80	75	50	68.3
18	70	70	60	66.7		18	60	40	60	53.3
19	80	80	80	80.0		19	70	50	60	60.0
20	80	90	80	83.3		20	80	60	80	73.3
Mean average				70.2		Mean average				72.4
ICC = 0.91, 95% CI [0.8-0.96], p<0.001						ICC = 0.64, 95% CI [0.24-0.85], p=0.0036				

5.3.3 Pre-operative manual templating assessment tool

The value, accuracy, and reliability of pre-operative templating is well recognised in THR. (217, 218, 219, 220, 221) Templating helps surgeons estimate the optimal implant size (femoral stem or acetabular cup) and position, evaluate the hip anatomy, and identify any potential problems before the operation (e.g., significant bone loss or previous operations or metalwork). Templating is most commonly performed using custom digital software on scaled digital radiographs from the Picture Archiving and Communication Systems (PACS). (220) However, it can be performed manually using acetate overlays of implant templates on either hard copies of radiographs against a lightbox, or by using printed scaled digital radiographs (222).

5.3.3.1 Methods

The templating assessment used in this study required participants to determine the implant sizes for a cemented femoral stem (Taperfit™), an uncemented femoral stem (TriFit™) and an uncemented acetabular cup (Trinity™) using acetate templates on an appropriately scaled AP pelvic radiograph printed on A3 sized paper. (Templates by Corin Group Ltd., The Corinium Centre, Cirencester, UK). Participants were allowed to make any markings on the printed radiograph, and upon completion were instructed to write the sizes of the templated components directly onto the paper. This exercise was designed to investigate the variance in THR component templated sizes within and between participants at a specialty registrar level of training. The performance of trainees in pre-operative templating is compared to consultants and fellows in chapter 7. The validity of pre-operative templating has previously been reported in THR, and therefore further testing of its accuracy and reliability are not required for use in this study. (217, 218, 219, 220, 221)

Figure 5-5: Pre-operative plain AP pelvis radiograph used for templating exercise.

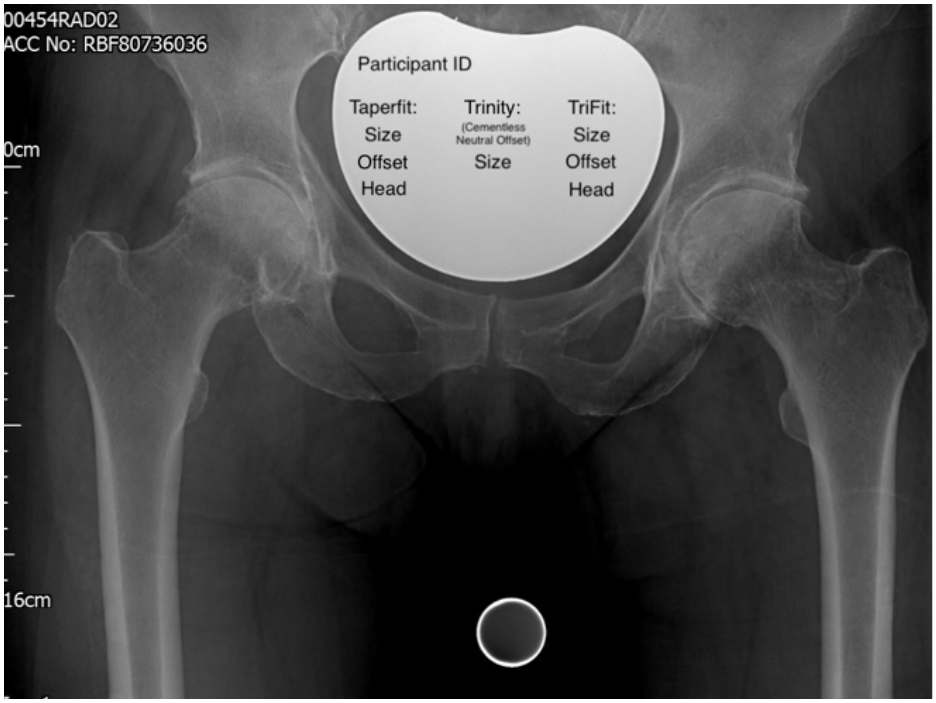
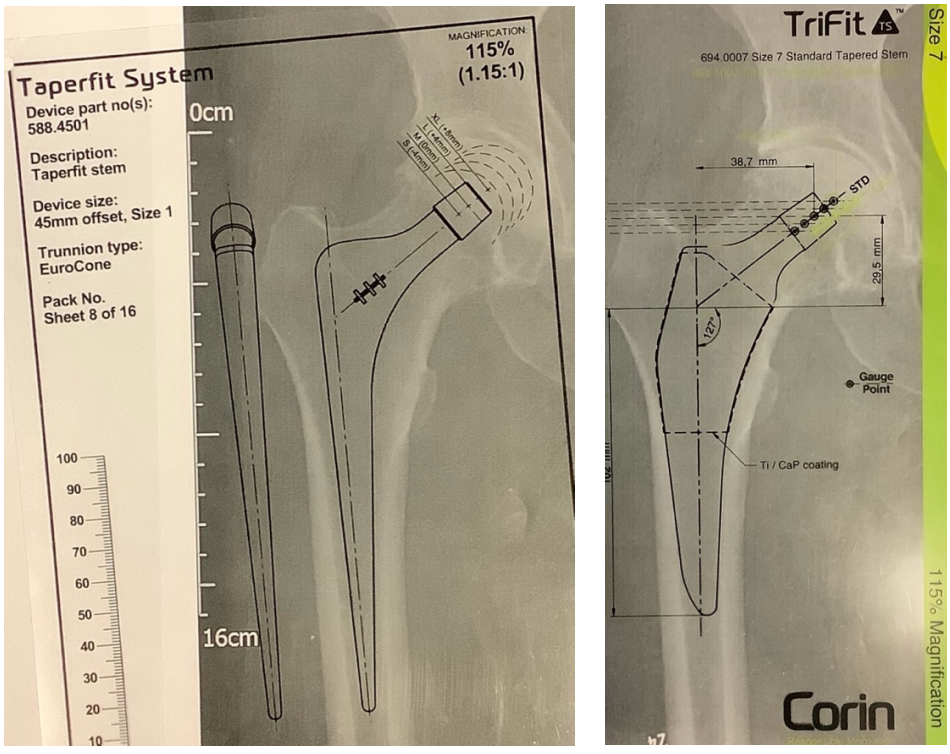


Figure 5-6: Pre-operative plain AP radiograph of right hip hemipelvis demonstrating overlying acetate femoral stem templates.

Cemented femoral stem template on left, and uncemented femoral stem template on right.



5.3.4 Skin marking assessment tool

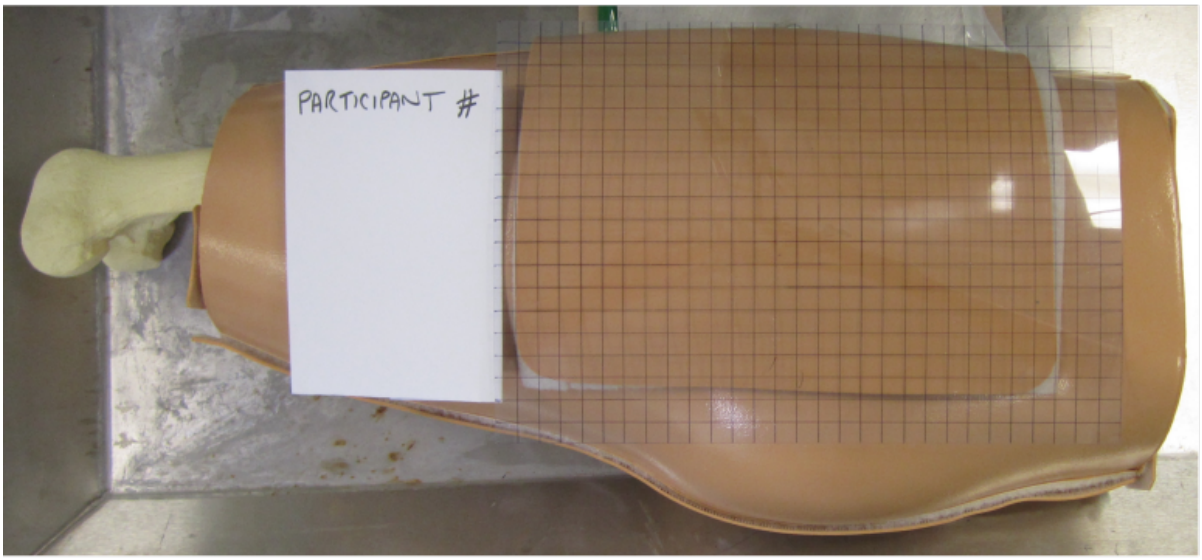
The expert consensus in chapter 4 highlighted that the skin incision and surgical approach was the most substantial for impact on patient outcome in primary elective THR. (174) The surgical approach used in THR has also been reported to significantly affect complication rates. (175, 202) Primary THR performed using an incision measuring less than 10cm has been termed minimally invasive. (223, 224) The theoretical advantages of using a minimally invasive incision and surgical approach including: a reduction in blood loss, transfusion requirements, post-operative pain, and length of stay have not been demonstrated in clinical studies. (224, 225) National Joint Registry (NJR) data indicate that the most common surgical approaches used for THR in the UK are the standard posterior (54.5%), and standard antero-lateral/Hardinge approaches (36.0%). (175)

5.3.4.1 Methods

This assessment tool aimed to determine both the length and curvature of planned skin incision made by surgeons using both the standard posterior and Hardinge surgical approaches to a primary THR. The equipment used for this assessment included: a standard hip arthroscopy simulator (Sawbones®, Pacific Research Laboratories, Sawbones Europe AB, Limhamn, Sweden); a 1cm square grid marked on an A4 sized colourless acetate; a roll of cling film; and a permanent marker. The hip simulator is a model of an adult left hip and thigh positioned on a stand in the lateral decubitus position (figure 5-7). A clean sheet of clingfilm was placed over the hip simulator before each exercise. The protocol for each experiment involved asking the participant to mark their planned skin incision (either posterior or Hardinge) over the hip using a permanent marker. The acetate grid would then be positioned over the long axis of the skin incision and a photograph was taken for subsequent analysis of the length and curvature of the marked skin incision. The clingfilm was removed and replaced for each experiment. Participants were asked to sequentially mark their planned skin incision for the Hardinge followed by the posterior skin incision. The performance of trainees in this assessment is compared to consultants and fellows in chapter 7.

Figure 5-7: Model used for skin marking assessment.

Hip model for skin incision exercise with overlying grid template



Hip model with skin marking for posterior surgical approach and overlying grid template.



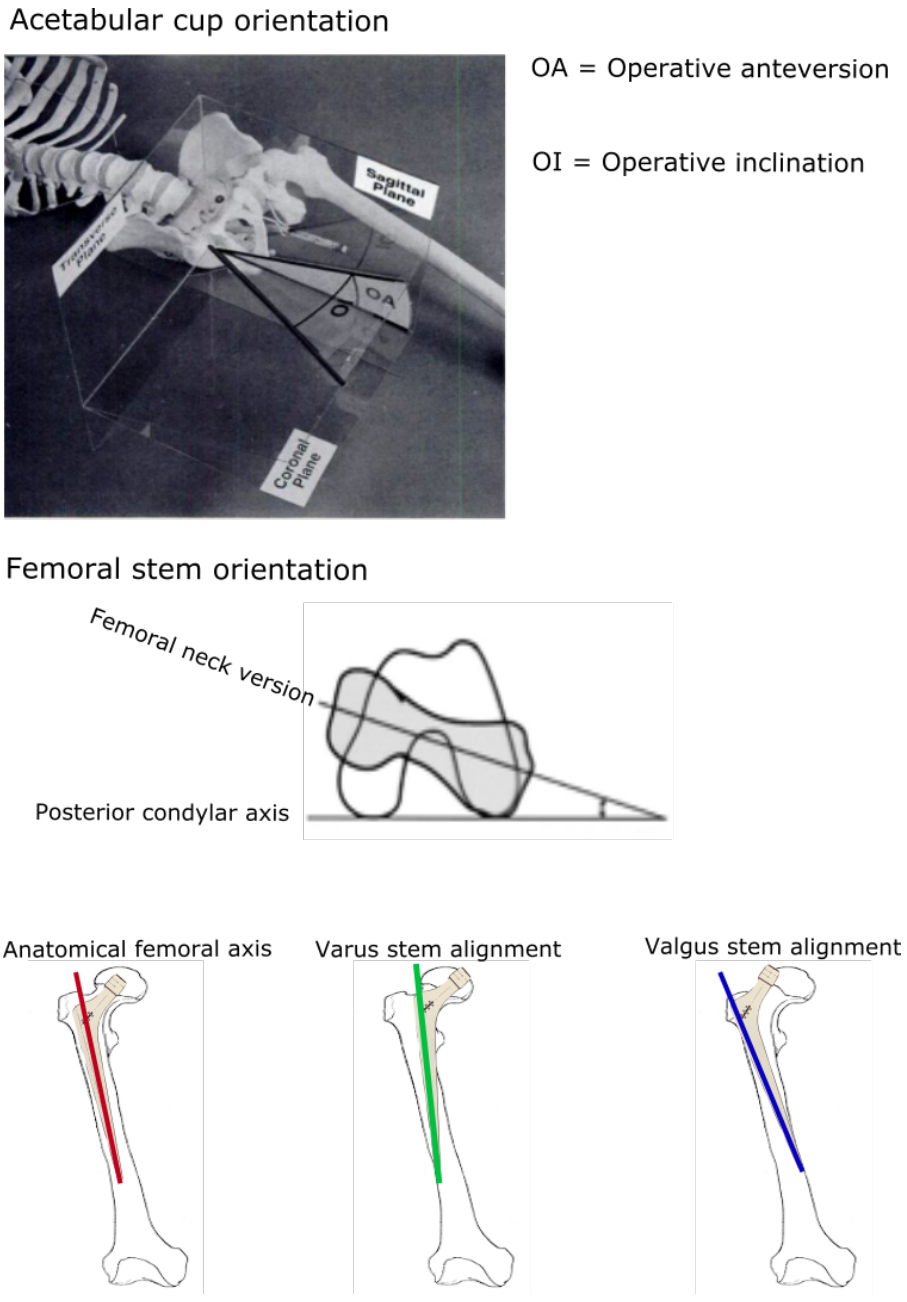
5.4Validation of a simulator for assessing implant orientation in THR

Aspects of this study have been published in Digital Health in December 2022. (226)

Accurate restoration of normal hip biomechanics during THR is known to result in improved patient function and satisfaction; reduced incidence of complications such as dislocation; and increased longevity of the implants. (99, 100, 101, 102, 103, 104) Contrary to this, component mal-positioning and mis-sizing may result in excessive wear, femoro-acetabular impingement (FAI), instability, dislocation, failure of fixation, leg length discrepancy, and poor functional outcomes. (112, 113, 114, 115, 116, 227) Accurate acetabular cup positioning and orientation is fundamental to restoring the hip centre of rotation (COR) and acetabular offset (AO). Accurate femoral stem positioning and orientation is fundamental to restoring leg lengths (LL) and improving the hip joint stability and range of movement (ROM). The femoral offset (FO) and neck shaft angles (NSA) are both properties of the prosthetic femoral stem, hence re-enforcing the importance of accurate component templating. The surgeon largely controls the orientation of the acetabular cup, and femoral stem version and alignment intra-operatively. The orientation of an acetabular cup may be described by its inclination and version, and this can be assessed anatomically, radiographically, or operatively. (228) Murray defined the operative acetabular anteversion (OA) as the angle subtended between the longitudinal axis of the patient and the acetabular axis in the sagittal plane (figure 5-8). The operative acetabular inclination (OI) is the angle subtended between the acetabular axis and the sagittal plane. OI is usually less than radiographic inclination (RI), as RI increases with increasing anteversion. The relationship between operative and radiographic acetabular cup orientation has previously been investigated. (229) The results of this study identified a mean difference between OI and RI of 5º (SD 5º), and between OA and RA of -8º (SD 8º). Femoral neck anteversion (FNA) is the angle subtended between the posterior bicondylar axis of the distal femur and a line up the femoral neck in the axial plane (figure 5-8). (230) Anatomical studies have reported a mean average FNA of 11.6º across male and female specimens. (231) Most surgeons aim to achieve 15º of FNA during THR, but a range between 10-20º is acceptable. (232) The concept of using a target combined anteversion

(acetabular cup OA and FNA), with a range between 30-50º has also been reported. (233, 234, 235) Femoral stem alignment (FSA) is the angle subtended between a line down the anatomical axis of the femur and a second line starting from the tip of the femoral stem travelling up the midpoint of the stem (figure 5-8). Traditional laboratory research methods for assessing acetabular and femoral component positioning include radiographic analysis and stereo photogrammetry. (236) However, both methods are time-consuming and do not provide real-time feedback on user performance.

Figure 5-8: Pictorial representation of acetabular (228) and femoral orientation angles.



5.4.1 Aims

To develop and validate the accuracy and reliability of a novel platform for measuring acetabular cup and femoral stem component orientations in real-time during simulated THR.

5.4.2 Methods

Ethical Approval

The online Healthcare Research Authority (HRA) decision tool was used to determine that formal ethical approval was not required for conducting this study as it did not involve human subjects, any form of randomisation, and the results are specific to the experimental settings in which they were conducted.

Participants

A total of four research staff from NDORMS (Windmill Road, University of Oxford, Oxford) and the Weatherall Institute of Molecular Medicine (Medical Research Council, University of Oxford, John Radcliffe Hospital, Oxford) volunteered to participate in the data collection in this study. Two researchers were assigned to the VR system set-up, calibration, and data collection (ST and MO). One researcher was assigned to the Vicon® system set-up, calibration, and data collection (JS). One (DJH) was assigned to component positioning and data collection from the manual measurement system.

Location

This study was conducted within the Oxford Gait Laboratory (Nuffield Orthopaedic Centre, Oxford University Hospitals NHS Trust, Windmill Road, Oxford).

Component orientation measurement systems, surgical equipment, and outcome metrics

The three component orientation measurement systems used in this study were:

1) The Vicon® optical motion capture (MoCap) system (Oxford Metrics PLC, Oxford, UK). The readings from this system were used as the 'gold standard' for comparison.

2) The VR platform developed using HTC Vive Pro® system hardware including two base stations with stands ('lighthouses') and two wireless trackers (Google, Mountain View, CA, USA).

3) The manual platform which used a bespoke box simulator in conjunction with a crossline laser (Tacklife™, Aukey Technology, Guangdon Province, China), digital angle gauge with magnetic base, and digital angle protractor (Wixey, Barry Wixey Development, Seattle, Washington).

The box simulator containing a synthetic adult hemi-pelvis and femur secured within a wooden frame (Sawbones®, Pacific Research Laboratories, Sawbones Europe AB, Limhamn, Sweden). The prosthetic implants used along with their respective introducers were a 56mm uncemented acetabular cup in the pelvis model (Trinity™, Corin Group Ltd., The Corinium Centre, Cirencester, UK), and a size 1 collarless polished tapered stem in the femur model (Taperfit™, Corin Group Ltd., The Corinium Centre, Cirencester, UK). The introducer for the acetabular cup screwed into the cup firmly, allowing negligible movement at the implant-introducer interface. However, the implant-introducer interface at the femoral stem allowed visible antero-posterior and varus-valgus movement. The degree of movement at the femoral implant-introducer interface is also investigated within this experiment. A modelling compound was used for simulated bone cement (Play-Doh, Hasbro, Pawtucket, Rhode Island, USA). This was injected into a prepared femoral canal using a high-pressure caulking gun with a long nozzle (Wolfcraft Gmbh MG600 PRO, Kempenich, Germany). See figure 5-11B.

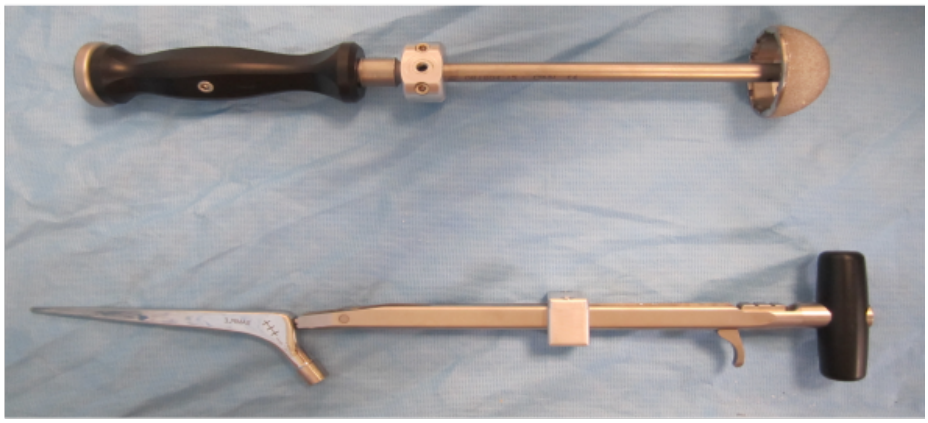
Figure 5-9: Instruments for manual component orientation measurement platform and acetabular/femoral implants on introducers.

Digital angle gauge (right) and crossline laser (left)



Acetabular cup and introducer (top)

Femoral stem and introducer (bottom)



The primary outcome measurements for these systems during the experiments were:

- **Pelvis model**: operative acetabular cup inclination (OI) and anteversion (OA) readings
- **Femur model**: femoral neck anteversion (FNA) and femoral stem alignment (FSA) readings
- **Femoral stem implant-introducer interface movement:** in the sagittal and coronal planes

Study set-up and protocol for data collection

Separate experiments were conducted on the pelvis, femur, and femoral stem-introducer. The model being tested was positioned in the centre of the gait laboratory, within full view of the MoCap and VR base stations. Physical passive markers were placed on the pelvis and femur models, and on the THR components, to allow calculation of three-dimensional orientation by the MoCap system. The MoCap system requires line of sight for each marker. Where this was not physically possible (e.g., the distal end of the femoral stem once implanted) virtual points were set using a wand prior to implantation. The VR wireless trackers and passive optical motion markers from the MoCap system were positioned on the synthetic bone models and surgical instruments as follows:

VR tracker positions

- Single tracker on baseplate or synthetic bone. See figure 5-10 B, F, G, and figure 5-11 C, F.
- Single tracker on either the acetabular cup or femoral stem introducer handle. See figure 5-10 A, F, G, and figure 5-11 A, D, E.

Vicon MoCap optical marker positions

- Pelvis synthetic bone
    - Two markers placed over each of the anterior-superior iliac spines (ASIS) and pubic tubercle (PT) to define the anterior pelvic plane (reference for measuring OA). See figure 5-10 B, D, F, G.
    - Three markers over the baseplate to define the virtual sagittal plane (reference for measuring OI). See figure 5-10 B - G.

- Acetabular cup introducer
    - Four markers were placed on the introducer handle: anterior and posterior both proximal and distal. See figure 5-10 A.

- Femur synthetic bone
    - Two markers placed on medial/lateral femur 15cm distal to tip of greater trochanter and a further two markers placed 15cm distal to this (reference for measuring FSA). See figure 5-11 C, F.
    - Posterior condylar axis marked with wand (reference for measuring FNA)
    - Centre of the intercondylar notch marked with wand (reference for measuring FSA)

- Femoral stem and introducer
    - A total of four markers were placed on the introducer handle: anterior and posterior both proximal and distal to the VR tracker. See figure 5-11 A.
    - Tri-cluster marker at head/trunnion junction. See figure 5-11 A, D, F.
    - The tip of stem was marked with the wand (reference for measuring FSA).
    - The lateral stem at intersection of neck axis (125°) was marked with the wand (reference for the NSA).

The segment and relative angle definitions used to calculate component orientation measurements for the acetabular cup and femoral stem are outlined in figures 5-12 and 5-13 respectively.

The crossline laser was mounted onto either the digital angle protractor in the pelvis model (figure 5-10 B, C, D, E) or onto the femoral stem introducer in the femur model (figure 5-11 D, E). The Vicon® and VR systems were calibrated by the respective research team members, and the manual system was calibrated by the lead researcher. In the pelvis model, calibration was performed by ensuring that the fulcrum of the digital angle protractor was centred over the acetabulum. This was

achieved by using a weighted femoral head as a plumb line suspended through the wooden cross bar and confirming this position using the crossline laser (figure 5-10 B, C). The digital angle gauge was placed on a level floor and reset prior to use. Measurement of OA is determined by moving the combined digital angle protractor and crossline laser anteriorly until the laser line is aligned with the introducer handle (figure 5-10 E). Measurement of OI is determined by placing the magnetic digital angle gauge on the introducer handle following implantation (figure 5-10 F). In the femur model calibration was performed by ensuring that the crossline laser was aligned down the femoral stem (figure 5-11 D). The FSA and FNA readings were then taken from a bespoke template referenced off the posterior condylar axis (figure 5-11 D).

The acetabular and femoral prostheses were manually implanted across a range of orientations representative of those expected intra-operatively. (114, 118, 233) The synthetic hemi-pelvis and femur bone models were securely attached to level baseplates to simulate the most commonly used patient position and surgical approach for performing a THR, namely the lateral decubitus position (figure 1) and posterior surgical approach (figure 2). (237) The acetabular cup was implanted within an intended range of OA between 10-40° at 5° increments, and OI between 35-60° at 5° increments. The digital inclinometer was used as a reference for acetabular cup OI, and a mechanical alignment guide (MAG) as a reference for OA. (236, 238, 239) The femoral stem was implanted freehand within an intended range of FNA between 0-30° at 5° increments, and FSA of neutral (0°), maximal varus, or maximal valgus. Simultaneous readings were taken from the MoCap, VR, and manual systems. The prostheses were removed and reimplanted for each individual experiment. The component orientation measurements collected for each experiment were the operative acetabular cup inclination (OI) and anteversion (OA) on the model hemi-pelvis; and the femoral neck anteversion (FNA) and femoral stem alignment (FSA) on the model femur.

Figure 5-10: Instruments and set-up for acetabular cup orientation measurements.

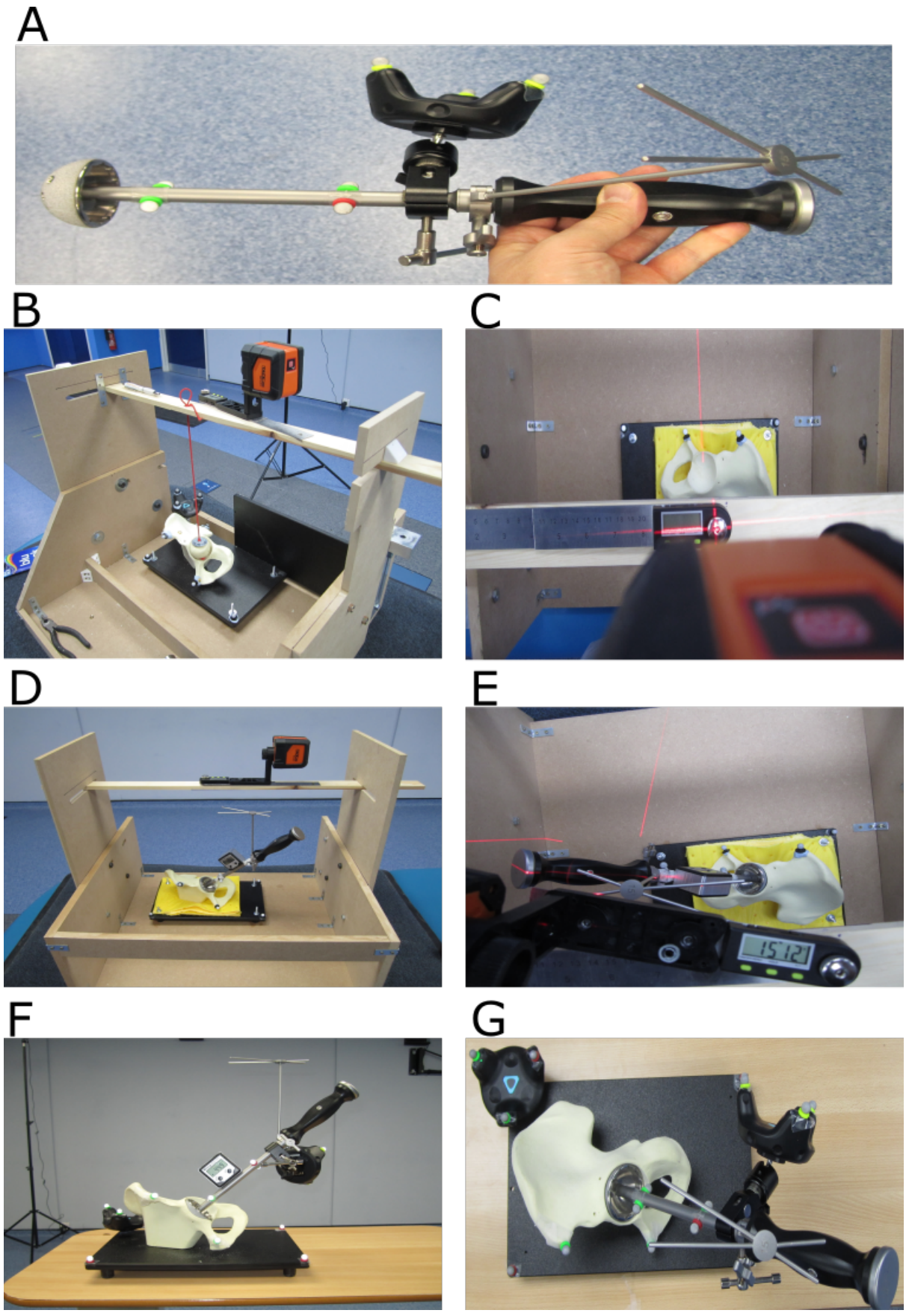


Figure 5-11: Instruments and set-up for femoral stem orientation measurements.

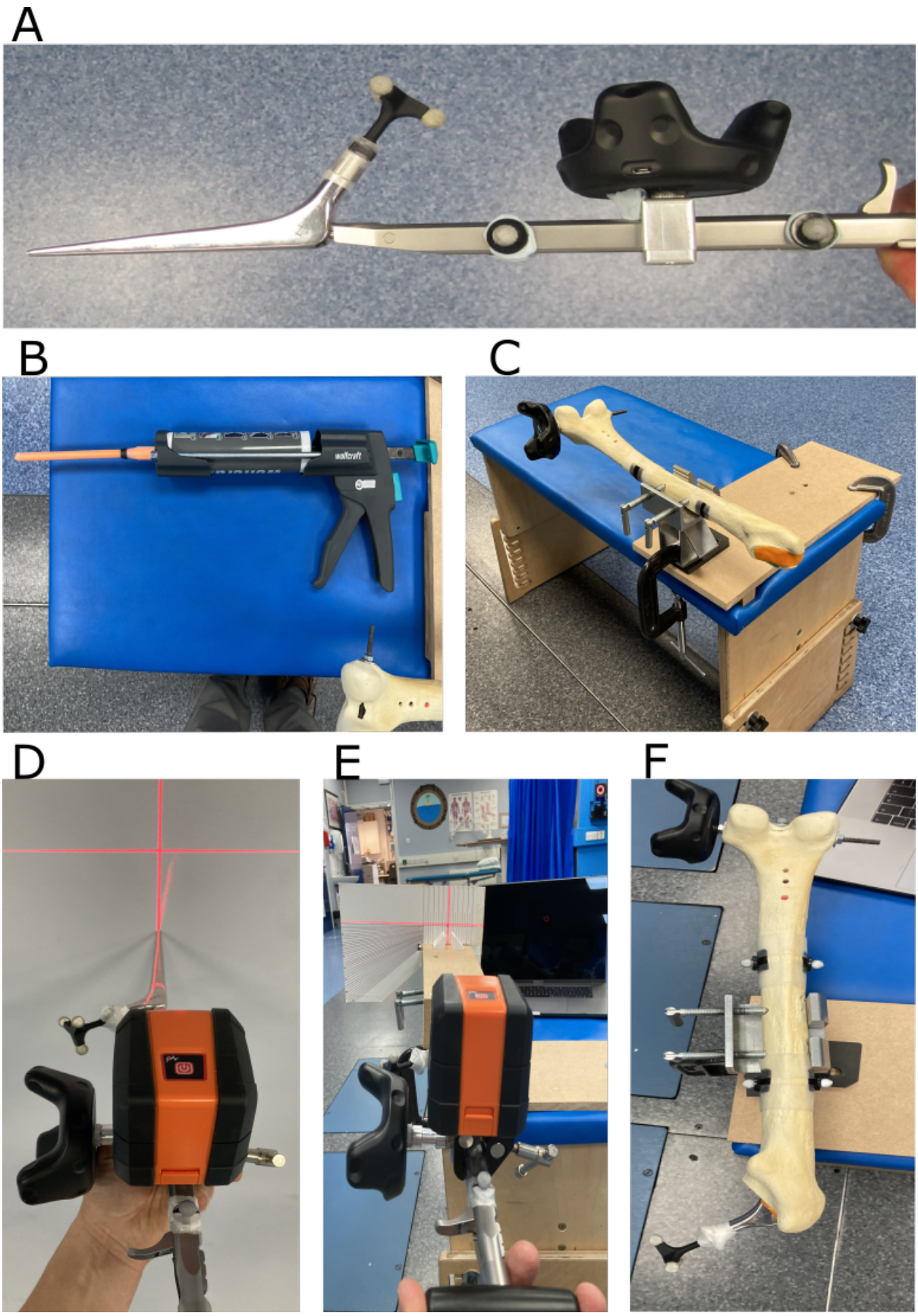
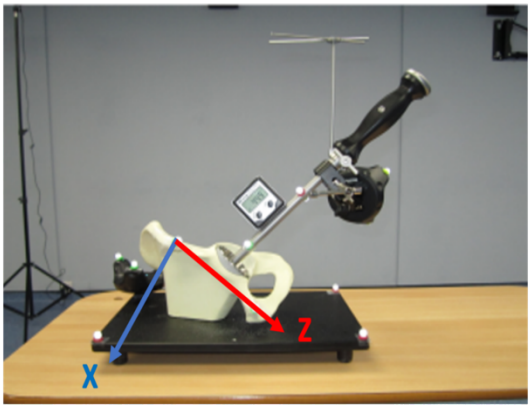
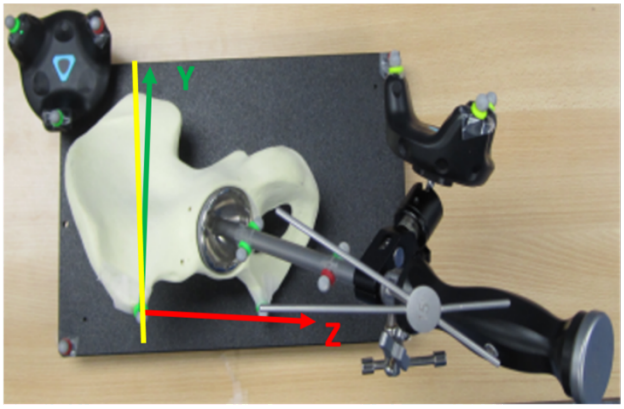


Figure 5-12: Segment and relative angle definitions used to calculate component orientation measurements for the acetabular cup.

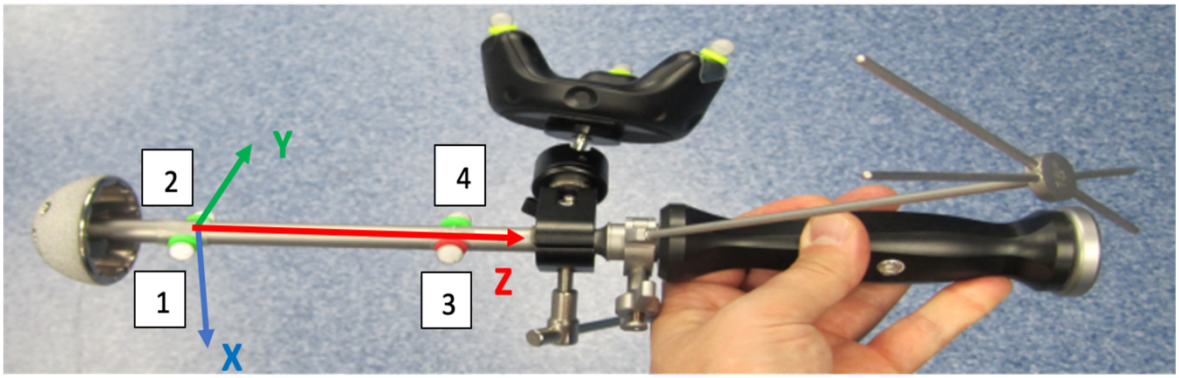
A. Segment definition for the pelvis





Origin: ASIS
Primary (z) axis: ASIS – PT
Sagittal plane: (ASIS – PT) x (ASIS – PSIS [yellow line])

B. Segment definition for the pelvis introducer



Origin: mid-point between points 1 and 2
Primary (z) axis: mid-point (1&2) – mid-point (3&4)
Sagittal plane: z x (1-2)

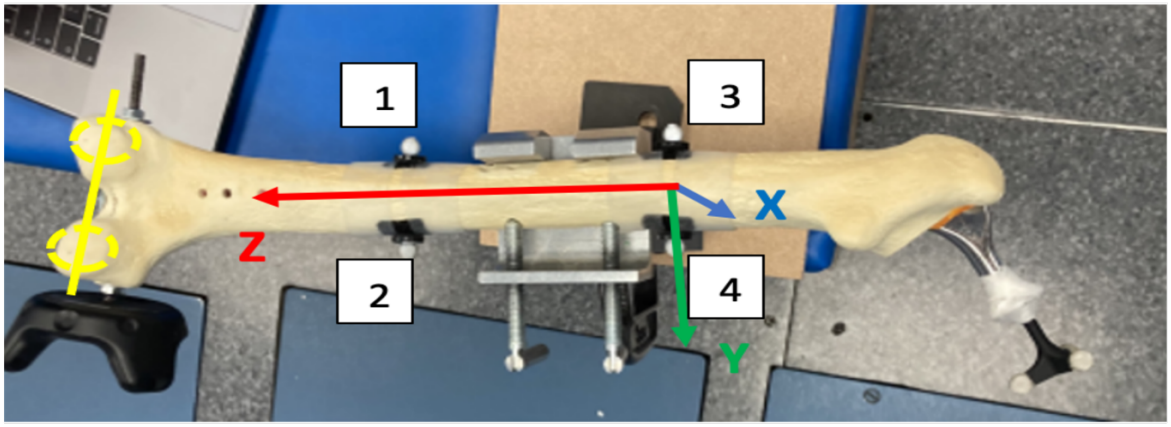
C. Angle definitions

Operative acetabular anteversion (OA) =
Relative angle between z axis of pelvis and z axis of pelvic introducer (about the y axis of the pelvis)

Operative acetabular inclination (OI) =
Relative angle between z axis of pelvis and z axis of pelvic introducer (about the x axis of the pelvis)

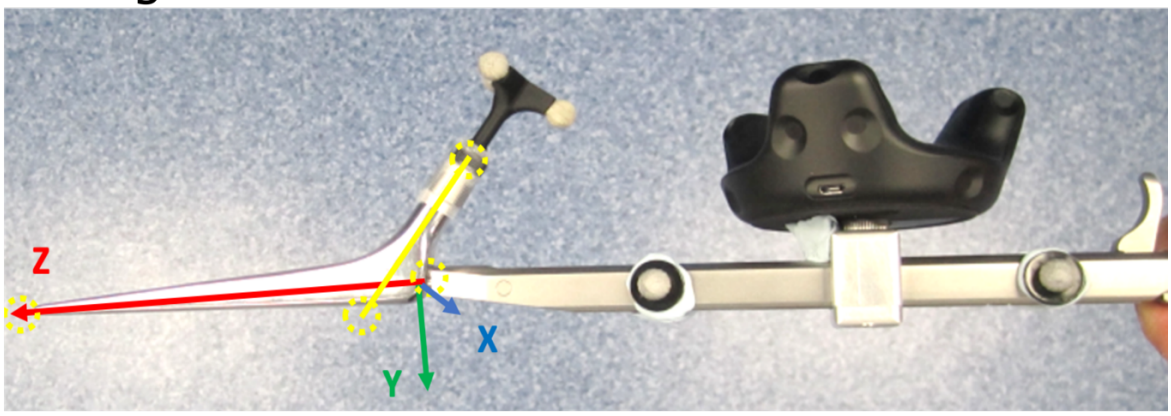
Figure 5-13: Segment and relative angle definitions used to calculate component orientation measurements for the femoral stem.

A. Segment definition for the femur



Origin: mid-shaft proximal (mid 3&4)
Primary (z) axis: (mid 3&4) – (mid 1&2)
frontal plane: z x bicondylar axis (yellow line)
Yellow dashed circles: virtual points

B. Segment definition for the femoral stem



Origin: proximal end of stem
Primary (z) axis: proximal – distal end of stem
frontal plane: z x neck of femoral implant (yellow line)
Yellow dashed circles: virtual points

C. Angle definitions

Femoral neck anteversion (FNA) =
Relative angle between y axis of femur and y axis of femoral stem (about the z axis of the femur)

Femoral stem alignment (FSA) =
Relative angle between z axis of femur and z axis of femoral stem (about the x axis of the femur)

Statistical analysis

Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The Pearson product moment correlation coefficient (PPMCC or Pearson's r) is used to determine the strength of any relationship between the readings from the gold standard Vicon® MoCap system and the VR/manual systems. For the purposes of this research, any PPMCC value <0.1 is considered a negligible correlation, 0.1 - 0.39 a weak correlation, 0.4 – 0.69 a moderate correlation, 0.7 – 0.89 a strong correlation, and >0.9 a very strong correlation. (240) Linear regression analysis is conducted on all significant relationships to determine the coefficient of determination (R^2) between readings from MoCap system and the VR/manual systems. Bland-Altman (BA) plots and statistics is used to assess the level of agreement between MoCap system and the VR/manual systems. Descriptive statistics is used for the femoral stem implant-introducer interface movement experiments. The significance threshold was set at 0.05 for all statistical analysis.

5.4.3 Results

5.4.3.1 Pelvis model

A total of 55 experiments were conducted investigating the acetabular cup orientation readings (OA and OI) using the MoCap/VR/manual systems and the pelvis model. The mean average difference in OA between the Vicon and VR system was 3.44°, 95% CI [-3.04–9.9°], p<0.001; and between the Vicon and manual system was 0.64°, 95% CI [-9.34-10.6°]. The mean average difference in OI between the Vicon and VR system was -0.01°, 95% CI [-4.51–4.5°], p<0.001; and between the Vicon and manual system was 1.24°, 95% CI [-4.29-6.77°]. Very strong positive correlations were demonstrated between the Vicon and VR system in both OA (PPMCC = 0.92, 95% CI [0.86-0.95], p<0.001), and OI (PPMCC = 0.94, 95% CI [0.9-0.97], p<0.001). A very strong positive correlation was found between the Vicon and manual system in OI (PPMCC = 0.92, 95% CI [0.86-0.95], p<0.001), and a strong correlation between the Vicon and manual system in OA (PPMCC = 0.84, 95% CI [0.75-0.91], p<0.001). Linear regression modelling demonstrated an adjusted R^2 of 0.82 for OA and 0.9 for OI when comparing the Vicon and VR systems; and of 0.7 for OA and 0.82 for OI when comparing the Vicon and manual systems.

Table 5-2: Summary of relationship and significance between the MoCap and VR/manual system readings for acetabular cup operative anteversion (OA) and inclination (OI).

System	Model	Measurement	Pearson R	95% CI	p value	Mean difference	Lower limit	Upper limit	Critical difference	Linear regression intercept	Linear regression coefficient
VR	Pelvis	OA	0.92	0.86-0.95	< 2.2e-16	3.44	-3.04	9.9	6.47	5.16	0.9
Manual	Pelvis	OA	0.84	0.75-0.91	5.14E-16	0.64	-9.34	10.6	9.98	4.43	0.81
VR	Pelvis	OI	0.94	0.9-0.97	< 2.2e-16	-0.01	-4.51	4.5	4.5	3.91	0.92
Manual	Pelvis	OI	0.92	0.86-0.95	< 2.2e-16	1.24	-4.29	6.77	5.53	6.31	0.89

Figure 5-14: Scatterplots and BA plots demonstrating the relationship between the MoCap, VR, and manual systems for measuring acetabular cup operative anteversion.

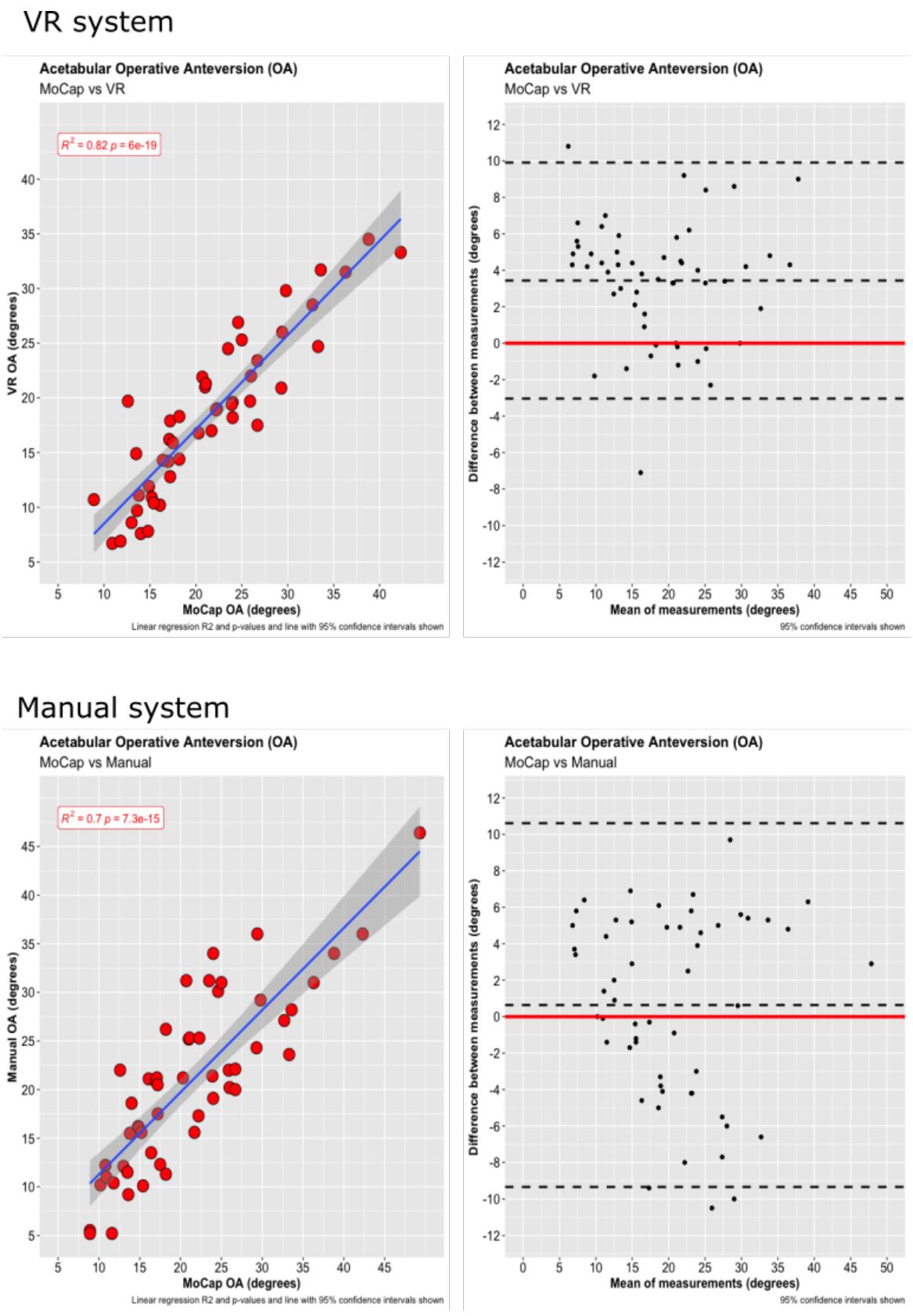
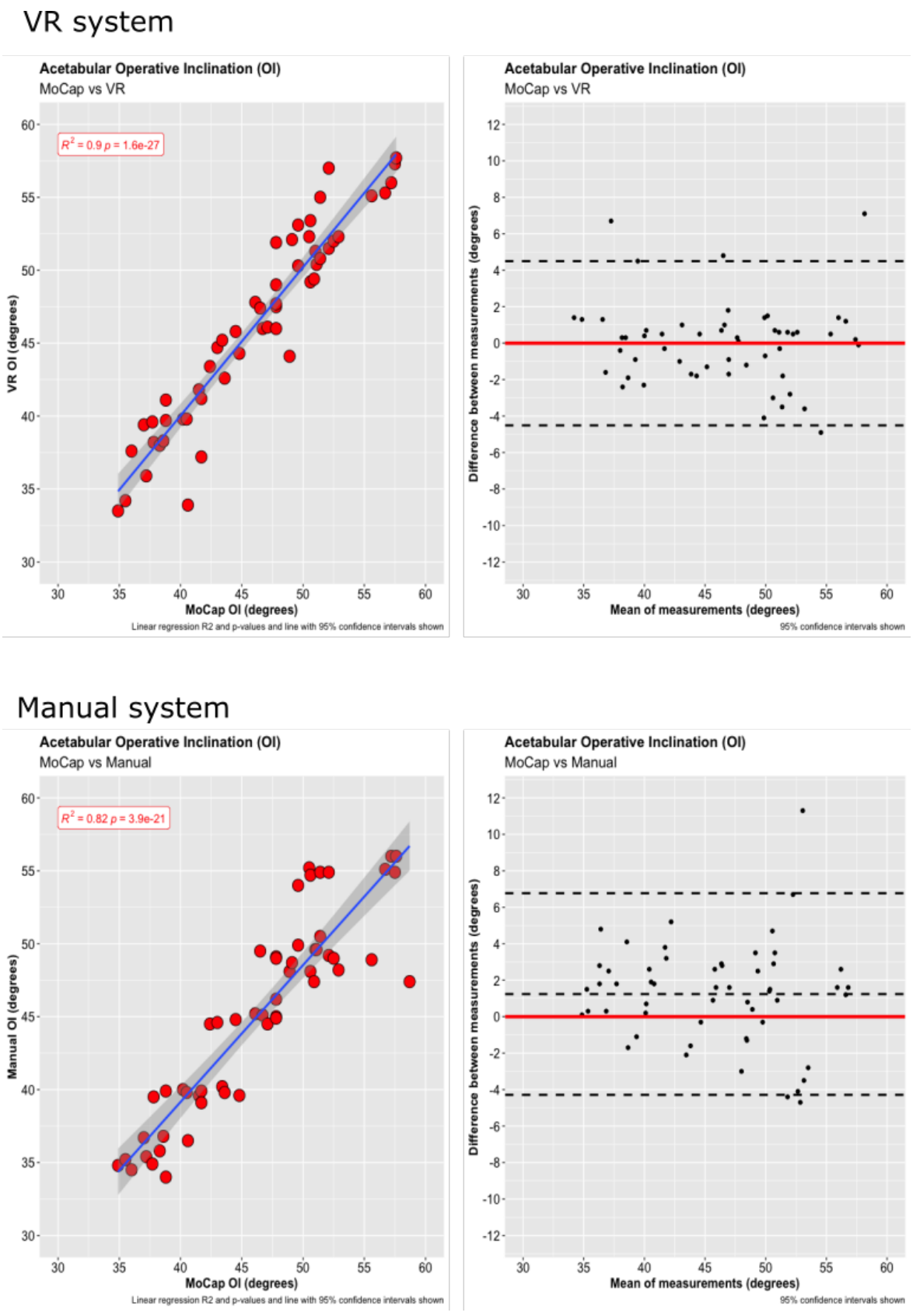


Figure 5-15: Scatterplots and BA plots demonstrating the relationship between the MoCap, VR, and manual systems for measuring acetabular cup operative inclination.



5.4.3.2 Femur model

A total of 68 experiments were conducted investigating the femoral neck anteversion (FNA) and femoral stem alignment (FSA) readings using the MoCap/VR/manual systems and the femur model. The mean average difference in FNA between the Vicon and VR system was -3.3°, 95% CI [-3.3–3.23°], p<0.001; and between the Vicon and manual system was 0.03°, 95% CI [-3.15-3.22°]. The mean average difference in FSA between the Vicon and VR system was 0.01°, 95% CI [-1.08–1.11°], p<0.001; and between the Vicon and manual system was 5.2°, 95% CI [-1.35-11.77°]. Very strong positive correlations were demonstrated between the Vicon and VR system in both FNA (PPMCC = 0.99, 95% CI [0.98-0.99], p<0.001), and FSA (PPMCC = 0.99, 95% CI [0.99-0.99], p<0.001). A very strong positive correlation was found between the Vicon and manual system in FNA (PPMCC = 0.99, 95% CI [0.98-0.99], p<0.001), and a strong correlation between the Vicon and manual system in FSA (PPMCC = 0.73, 95% CI [0.59-0.83], p<0.001). Linear regression modelling demonstrated an adjusted R^2 of 0.98 for FNA and 0.98 for FSA when comparing the Vicon and VR systems; and of 0.98 for FNA and 0.54 for FSA when comparing the Vicon and manual systems.

Table 5-3: Summary of relationship and significance between the MoCap and VR/manual system readings for femoral neck anteversion (FNA) and femoral stem alignment (FSA).

System	Model	Measurement	Pearson R	95% CI	p value	Mean difference	Lower limit	Upper limit	Critical difference	Linear regression intercept	Linear regression coefficient
VR	Femur	FNA	0.99	0.98-0.99	< 2.2e-16	-0.04	-3.3	3.23	3.27	1.24	0.92
Manual	Femur	FNA	0.99	0.98-0.99	< 2.2e-16	0.03	-3.15	3.22	3.18	0.13	0.99
VR	Femur	FSA	0.99	0.99-0.99	< 2.2e-16	0.01	-1.08	1.11	1.09	0.15	0.98
Manual	Femur	FSA	0.73	0.59-0.83	1.12E-11	5.2	-1.35	11.77	6.56	4.87	1.93

Figure 5-16: Scatterplots and BA plots demonstrating the relationship between the MoCap, VR, and manual systems for measuring femoral neck anteversion.

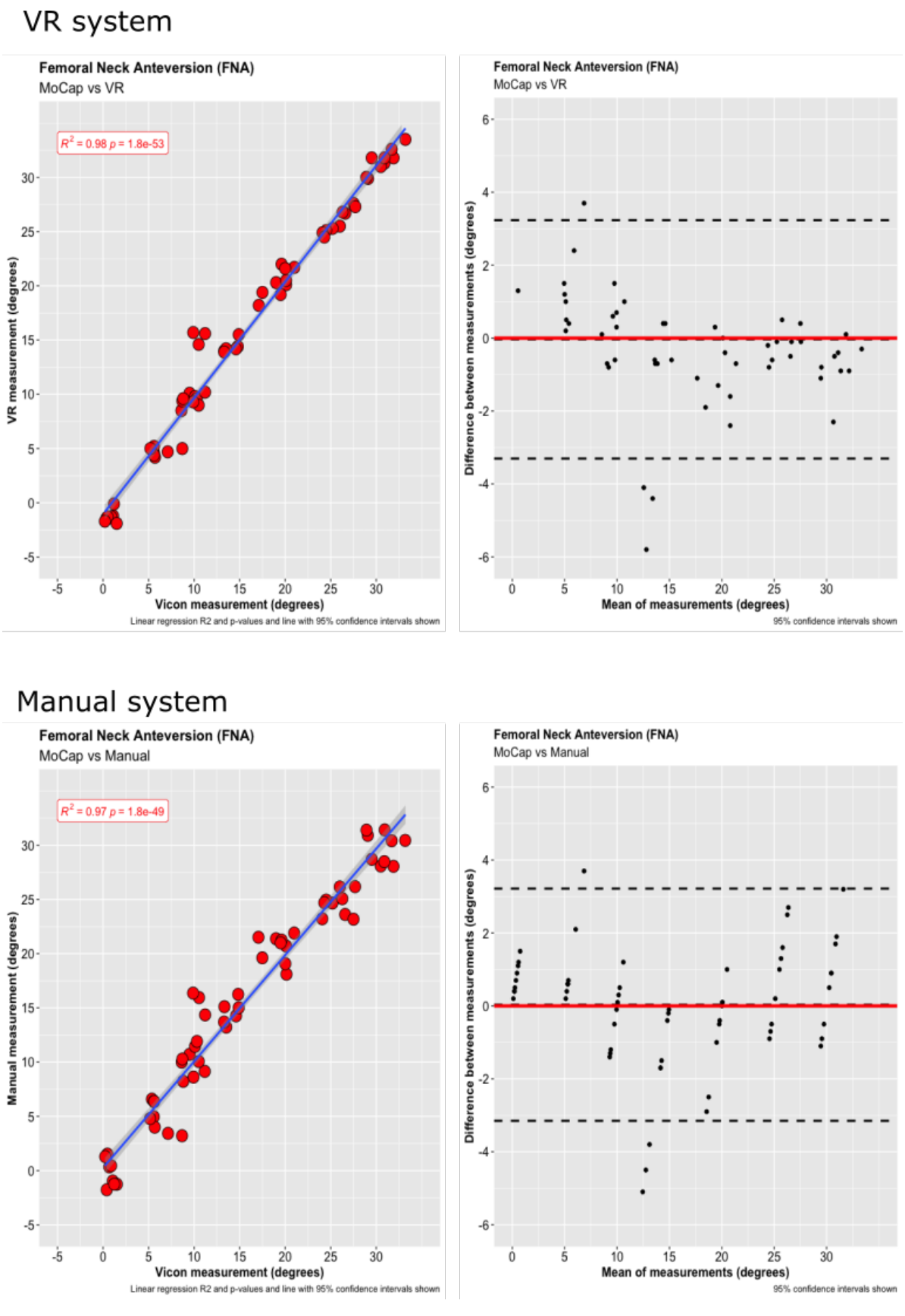
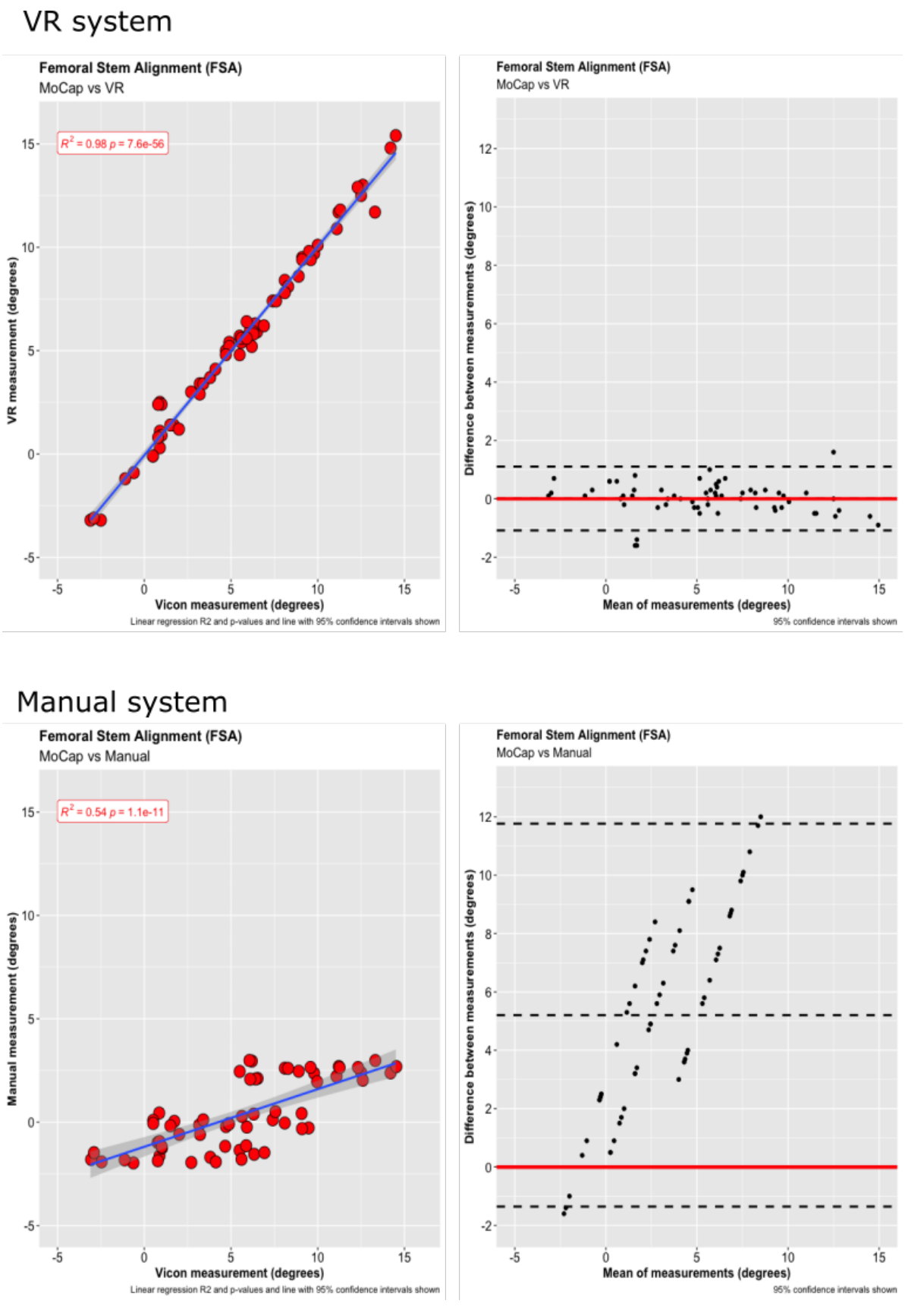


Figure 5-17: Scatterplots and BA plots demonstrating the relationship between the MoCap, VR, and manual systems for measuring femoral stem alignment.



5.4.3.3 Femoral stem implant-introducer interface model

The femoral stem is held on the introducer by an oblong shaped metallic extension at the distal end of the introducer, which is inserted into a reciprocal hole in shoulder of the prosthesis. Once in position a button on the side of the introducer handle is depressed to 'lock' the stem in position (Figures 5-9 and 5-11 A). Following stem insertion, a release trigger on the opposite side of the introducer handle is squeezed to release the capture mechanism. The oblong shape of the locking interface provides good rotational stability, but movement in both the sagittal (AP) and coronal plane (varus/valgus) remains possible. The aim of this set of experiments is to determine how much movement is possible at the femoral stem implant-introducer interface. A total of 27 experiments were conducted with the following conditions:

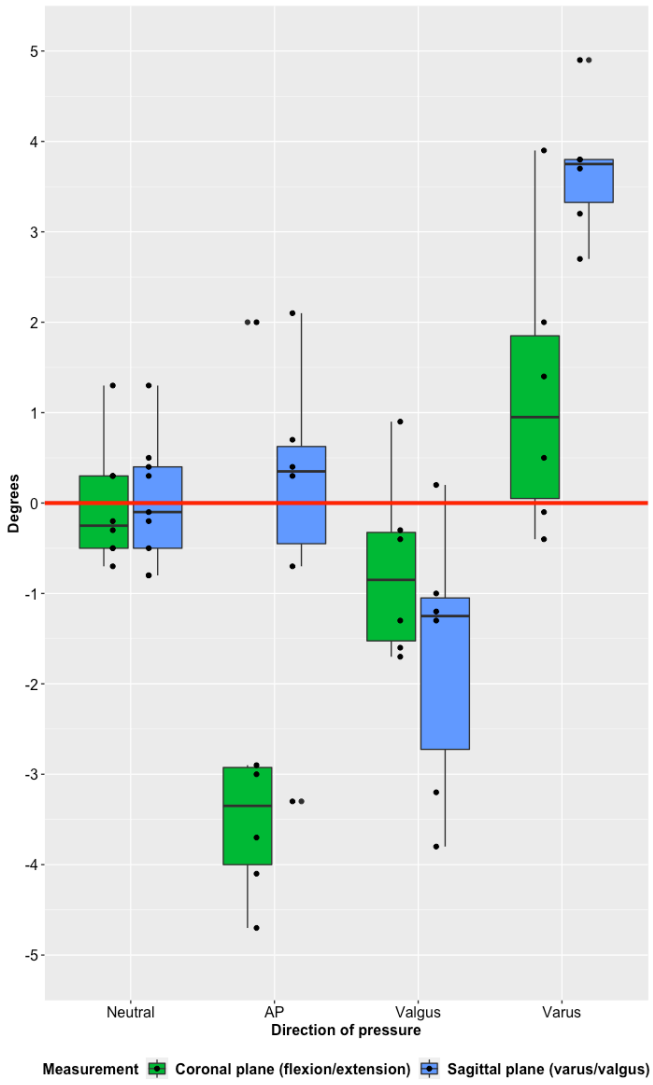
1) Neutral position with no pressure on the stem (n=9)
2) AP – with pressure applied over the anterior femoral stem (n=6)
3) Valgus - with pressure applied over the medial femoral stem (n=6)
4) Varus pressure - with pressure applied over the lateral femoral stem (n=6)

The MoCap system was the only system used for these experiments. This is because it is the only validated system for three-dimensional positional assessment, in comparison to the VR and manual systems, which are both experimental. For all experiments the femoral stem was loaded and locked on its introducer, and measurements of the femoral stem alignment relative to the introducer were taken in the sagittal (flexion/extension) and coronal (varus/valgus) planes. The results demonstrate a high degree of precision in both coronal and sagittal plane alignment of the femoral stem implant-introducer interface when held in a neutral position. However, varus/valgus pressure changes the alignment of the implant-introducer interface predominantly in the coronal plane from a mean average of -1.71 to 3.68 degrees (range 5.39°). Antero-posterior pressure was also found to change the alignment of the implant-introducer interface predominantly in the sagittal plane by a mean average of 2.7 degrees.

Table 5-4: Summary results of the femoral stem implant-introducer interface experiments.

	Sagittal plane (flexion/extension)			Coronal plane (varus/valgus)		
	Mean	**Median**	**Range**	**Mean**	**Median**	**Range**
Neutral	-0.04	-0.25	-0.7-1.3	0.01	-0.1	-0.8-1.3
AP pressure	-2.7	-3.35	-4.7-2	-0.08	0.35	-3.3-2.1
Valgus pressure	-0.7	-0.85	-1.7-0.9	-1.71	-1.25	-3.8-0.2
Varus pressure	1.22	0.95	-0.4-3.9	3.68	3.75	2.7-4.9

Figure 5-18: Boxplots demonstrating the degree of movement at the femoral stem implant-introducer interface under specific conditions.



5.5Discussion

5.5.1 Summary and relevance of findings

Several educational frameworks and theories have been used to describe levels of cognitive development and learning. Examples include Bloom's cognitive taxonomy, Moore's expanded outcomes framework, and Millers' Pyramid (241, 242, 243, 244) Advanced descriptive taxonomies such as Moore's expanded outcomes framework account for a wide spectrum in the levels of learning from simple participation in educational activities, through to the impact of any acquired knowledge and skills on public health. Although the exact number and definition of levels within each of these frameworks differs, the principles are that lower-level learning is associated with participation in educational events, knowledge acquisition and recall; mid-level learning is associated with the practical application of this knowledge, and higher order learning is associated with the attainment of competence, problem-solving capabilities, and the ability to teach others.

Although no single assessment can fully determine the overall performance level of an individual, the assessment tools specific to primary THR which have been developed within this study test a broad range of procedure-specific cognitive and technical skills performance. It is important to consider the cost, feasibility, validity, and reliability when designing and utilising assessment tools. Well-designed MCQs are capable of effectively quantifying the learning following attendance at an educational event. (245) MCQs are therefore one of the most widely used and cost-effective assessment tools in medical education. (246) The benefits of MCQs include that they are practically easy to administer and score, with very little supervision or expertise required. In this study the Angoff methodology was used for MCQ score-setting, which provides external validation and reassurance that the structure, content, difficulty, and pass mark of the questions are justified for use in assessing a specialty trainees core knowledge in THR. Applying the Angoff methodology to the pre-and post-module MCQs indicates that both tests were judged to be of similar levels of difficulty, with a cut-off pass mark of 70.2% and 72.4% respectively. The ICC values also indicated excellent and fair inter-rater reliability for the pre- and post-module MCQs, respectively.

The mid-order levels of participant performance are tested using the templating and skin marking exercises, which both require participants to 'show how' they can use their knowledge. Studies have demonstrated a high intra- and inter-observer reliability in pre-operative THR digital templating for surgeons of varying experience levels. (247, 248) However, no published clinical or laboratory-based studies have investigated the relationship between surgical grade and length of skin incision used in primary THR, and this is a novel assessment tool reported within this research.

The mid to higher order levels of performance, which require situational awareness in addition to the application of procedure-specific knowledge and skills, are tested in the component positioning assessment. Development and validation of two novel and cost-effective methods for determining real-time quantification of both acetabular and femoral component orientation in simulated THR have been undertaken in this study. The benefits of using a live feedback mechanism for accurately determining component orientation in combination are that participants may practise and optimise their psychomotor skills of THR in the safety of a simulated environment before translating these skills into the operating theatre. The total cost of the Vicon® MoCap system used in this study is approximately £200,000 GBP, in comparison to the VR system hardware which costs approximately £1500 GBP, and the manual box simulator hardware which costs approximately £100 GBP excluding the synthetic bone models. The cost and technical complexity of using the Vicon® MoCap system, which was used as our gold standard comparator, precludes its routine use in surgical training. (249) A reduction in cost and improved access to VR technologies over the past decade has vastly increased their use and application for both research, commercial and recreational activities. One study has highlighted that the use of augmented (AR) and virtual reality (VR) in the healthcare sector had a market value of approximately $2billion USD in 2020, which is expected to increase exponentially with future demand in this field. (250) Medical and surgical training and education are only one application of this technology (66, 75, 78, 79, 92, 251, 252), with anatomy teaching also being a well cited use. (253, 254, 255) Other reported applications of AR/VR technology in the healthcare setting include cognitive and physical rehabilitation following stroke or traumatic brain injury. (256, 257, 258) VR trackers have been used for estimating object position and orientation in

several applications to date. (92, 259, 260, 261) One study assessed the agreement between the HTC Vive® VR system and the Vicon® MoCap system when measuring lumbar postural changes, and reported a high degree of accuracy in position (0.68+/-0.32cm) and orientation (1.64+/-0.18°) estimation. (259) Another study reported a high degree of accuracy in pose estimation for both static and multiplanar exercises. (261) Studies have also reported on the use and accuracy of AR-based systems for determining acetabular cup orientation in both simulated and clinical settings. (92, 262, 263) An experimental AR system based on the Hololens™ headset (Microsoft®, Albuquerque, New Mexico, USA) was reported to demonstrate a translational accuracy of <1mm, with an orientation accuracy of 0.2° in inclination and 0.9° in anteversion during simulated THR. (92) Another study investigated the accuracy of an AR system versus manual goniometer for determining acetabular cup orientation in a group of 54 patients undergoing primary THR via the direct anterior approach in a supine position. (262) The authors report a mean absolute difference between the intra-operative AR and post-operative CT scan measurements of 2.1°+/-1.5° in inclination and 2.7°+/-1.7° in anteversion. A subsequent randomised controlled trial aimed to assess the accuracy of this AR system versus traditional mechanical alignment guides (MAGs) in measuring acetabular cup orientation in a group of 46 patients undergoing primary THR via the Watson-Jones approach in a lateral decubitus position. (263) The AR system in this study was calibrated using marker pins inserted into the iliac crests prior to moving patients from a supine into a lateral decubitus position. The mean difference between the AR system and post-operative CT scan measurements was 1.9°+/-1.3° in acetabular cup inclination, and 2.8°+/-2.2° in anteversion. Statistically significant, but not clinically important, differences were noted in acetabular cup inclination between systems, with conventional MAGs overestimating this measurement in comparison to the AR system. No significant differences were found between the AR system and MAG measurements in anteversion. The difference in inclination measurements may possibly be explained by the surgeon not fully accounting for intra-operative pelvic sag when using the MAG, which is a known factor for acetabular cup mal orientation in THR with patients in a lateral decubitus position. (201) The main limitations of using this AR-based system for assessing acetabular cup orientation in the clinical

setting are shared with established robotic-assisted navigation systems. These include the need for obtaining pre-operative CT scans, and often the intra-operative insertion of marker/array pins into bony reference points to allow system calibration, especially when patients are in a lateral decubitus position.

The results of this study indicate that the VR system has a mean orientation accuracy of -0.01° in OI and 3.44° in OA, with very strong positive correlations demonstrated in both OI and OA. The increased error observed between systems in determining acetabular cup OA in comparison to OI may relate to minor inaccuracies in defining the anterior pelvic plane during system calibration. This plane is used as the pelvic segment reference to calculate OA relative to the acetabular cup introducer segment which was more challenging to recreate virtually using the handheld VR trackers in comparison to the sagittal plane represented by the model baseplate from which OI is referenced. No studies have reported using a VR system for determining femoral stem orientation in simulated THR, and this aspect of our research is novel. We report a mean average difference of -0.04° in FNA and 0.01° in FSA between the Aescular VR and Vicon® MoCap systems, with very strong positive correlations between these systems in both FNA and FSA. The results indicate that the VR system is an adaptable, highly accurate and reliable tracking system, which may be modified for use in a range of simulated surgical training and educational purposes, particularly in orthopaedic surgery where accurate implant positioning and orientation are known to be critical to implant function, survivorship, and patient outcomes. Further refinements in the calibration process may result in improved accuracy of this system in assessing implant orientation.

The manual method of assessing implant orientation in this study has also yielded promising results. This system is the most austere and user friendly by a considerable margin. Calibration of the system takes a few minutes and does not require any specialist knowledge or skill. The bespoke box simulator required for this system is constructed of widely available and relatively inexpensive synthetic bone models of a hemi-pelvis and femur secured within a custom frame. The digital angle gauge, protractor, and crossline laser are also widely available and cheap to purchase. The mean

average difference between the MoCap and manual systems was 0.64°and 1.24 in OA and OI readings, with strong and very strong positive correlations respectively. The 95% CIs reported in the measurements of OA and OI by the manual system fall within the acceptable margins of error for cup orientation of +/-10° for inclination and anteversion (114), and therefore justify using the manual system for assessing cup orientation in simulated THR. In relation to femoral stem component orientation, the manual system demonstrated a mean average difference in FNA readings from the MoCap system of 0.03° and 5.2° in FSA, with very strong and strong positive correlations demonstrated between these systems in both FNA and FSA, respectively. Although the mean average FNA readings between the manual and MoCap systems suggest that the manual readings are within an acceptable clinical range of +/-5° (232), the FSA readings from the manual system are not accurate enough for assessing stem orientation in simulated THR. Furthermore, studies have also reported that slight malalignment (0+/-3º) of both uncemented and cemented femoral stems are not associated with significant adverse patient outcomes following THR. (264, 265) Overall, the results demonstrate that the precision of the manual system in determining acetabular cup OA and OI, and FSA are slightly less than the VR system but still within an acceptable confidence interval. The manual system reported equivalent and acceptable accuracy in determining FNA, but not FSA in comparison to the VR system.

5.5.2 Limitations of study

Evidence suggests that writing effective MCQs is a creative skill that requires specific training and practice. (266) Specific training was not undertaken prior to creating the MCQs used in this study, although the process of practice and refinement was utilised prior to establishing the final versions of the MCQs. Conducting the modified Angoff methodology of standard setting for the written MCQs is a form of external appraisal of the quality of questions and may justifiably be considered a mitigating factor for the lack of formal training. One main limitation of using the modified Angoff method is that expert judges often struggle to conceptualise a borderline candidate. (213) Robust and detailed analysis of the reliability and validity of these MCQs, such as calculation of the inter-and

intra-rater reliability, and difficulty and discrimination indices were also not undertaken as part of this study. (267, 268) This is because these tests are only being used as a formative assessment as part of a research study, and not a summative assessment towards any formal qualification of competency. Further testing and modification of these assessment tools should certainly be considered if this training module were to be formally recognised within a training program.

One limitation of the simulation models used in this study includes a lack of soft tissues. Dry synthetic bones without simulated muscles were used in the acetabular and femoral preparation practical sessions. Simulation models with muscles were used in the acetabular cup positioning exercise, but not the femoral stem positioning exercise. The limitation to this is that the transverse acetabular ligament (TAL), which was not present in the pelvis model used, is commonly used as a patient-specific intra-operative anatomical landmark to guide the version of acetabular component positioning. (117, 269)

Experiments of the femoral stem implant-introducer interface have highlighted up to 5° freedom of movement at this interface with gentle pressure applied in both the coronal and sagittal planes. One mitigating factor for this degree of movement may be the bespoke bracket for the VR tracker, which was attached firmly to the femoral introducer. This may have negatively affected the locking mechanism of the femoral stem on to the introducer. Further experiments without the addition of this bracket may be useful to characterise this degree of movement at the implant-introducer interface in detail. Alternative implants and surgical equipment may also be tested to provide a more comprehensive understanding of relative stabilities of the femoral stem implant-introducer interfaces across a range of equipment.

5.6Conclusions

To deliver an effective and efficient training module, it is vital to concentrate on the critical learning objectives relevant to the subject. The content of this simulation-based training module has been specifically designed in response to the results of an expert consensus identifying the key steps of a THR both for patient outcome and difficulty in teaching on the job. This training module provides a focussed, evidence-based, and structured attempt to deliver the core scientific knowledge, theory, and basic practical skills training required of an orthopaedic trainee in primary THR. The practical simulation-based technical skills sessions have been designed specifically to allow trainees the opportunity to practise the key steps of this operation using a range of real-world surgical instruments in the safety of a non-clinical environment and use validated methodology to assess performance. This structured training module should theoretically maximise the opportunities for trainees to learn and practice the key knowledge and technical skills relevant to this operation. The combination of teaching modalities including didactic lectures, simulation-based practical skills sessions, and delegate workbook collectively provide a comprehensive and enduring training guide in primary THR. The overwhelmingly positive participant feedback received following completion of this training module reflects the trainees' attitudes and demand for this type of training. The next chapter focusses upon designing and validating a motion analysis system capable of quantifying intentional hand movements in surgeons when performing a range of tasks, including procedure-specific tasks in THR. This system provides a further objective measurement of surgical skill and manual dexterity in surgeons across a range of experience levels in addition to the assessment tools outlined in this chapter.

6 Developing and validating a novel wireless motion analysis system for assessing technical surgical skill.

6.1 Introduction & aims

Manual dexterity is a critical factor in determining technical surgical skill. (60, 270, 271) Hand motion analysis systems and metrics have been widely used to generate objective quantifiable surrogate markers of manual dexterity and surgical technical skills performance. (272, 273) Construct validation studies have used upper limb motion analysis as a primary outcome measure for differentiating the performance of novice versus expert surgeons in laparoscopic (274, 275), arthroscopic (57, 59, 107, 272, 276, 277), and open (273) simulated surgical tasks. Movement count (62, 273) and path length (273) are commonly quoted motion analysis metrics in surgical studies, but recently novel force-based metrics (275, 278, 279) have also been shown to correlate with surgeon experience. Instrumented motion tracking systems may use mechanical, optoelectronic, electromagnetic, or inertial sensor technology to capture motion data. (56, 272, 280, 281, 282) The specialised sensors used in each system are attached to anatomical landmarks or surgical instruments and record specific motion data parameters during set tasks or procedures. This motion data is analysed using computer software programmes to generate objective metrics describing the sensors motion in time and/or space. Objective motion metrics are therefore determined by a combination of the tracking system used, data parameters recorded, and the methodology used to analyse this data. Considerable heterogeneity exists in the motion parameters recorded by mechanical, optoelectronic, electromagnetic, or inertial sensors, which impart specific advantages and limitations in using each technology. No single system is capable of fully capturing the complexity of human upper limb movements. When selecting or developing a motion analysis system it is important to consider the setting and purpose for which it is used, as considerable variations exist in the cost, complexity, and feasibility of using these systems for clinical or research purposes. (281)

The aim of this chapter is to develop and validate a low-cost motion analysis system for use in both laboratory and clinical environments which can objectively quantify intentional hand motion across a range of tasks. The metrics generated by this system are used in subsequent study chapters to objectively determine and differentiate the performance of surgeons during primary THR. These requirements preclude the use of mechanical, optoelectronic, and electromagnetic systems in the clinical environment of an operating theatre as they are not feasible for use due to sterility, line-of-site, and wiring issues, respectively. However, inertial sensor technology is widely available, low-cost, discrete, portable, unrestricted by line-of-sight or wires, and has been used extensively for human motion analysis research, including within the domain of clinical surgery. (57, 281) These are the primary reasons for using inertial sensor technology hardware in developing this novel wireless motion analysis system. Quantitative output metrics from the novel wireless motion analysis system are compared to those obtained from a validated wired electromagnetic motion tracking system. The content and concurrent validity of both wired and wireless motion analysis systems are assessed through a series of three linked studies which use both systems to collect hand motion data simultaneously when performing tasks in both a laboratory and clinical environment. An overview of both the wired and wireless motion analysis systems used in this research and the principles of signal processing is outlined, as these systems are used within all three linked studies.

6.1.1 Motion analysis systems

The application, interpretation and limitations of motion analysis systems is based upon several principles in physics. These include the definition of and relationship between time, distance, speed, displacement, acceleration, velocity, mass, and force and the concepts of scalars, and vectors, position, orientation and pose. It is beyond the scope of this research to fully describe these factors, but a broad understanding of how each is calculated and interpreted is critical to motion analysis signal processing. Vectors are quantities that are fully described both magnitude and direction, but do not have position. (283) Displacement, velocity, acceleration, and force are all examples of a vector. Scalars are quantities that are fully described by magnitude (numerical value) alone. Time, distance, speed, and mass are all examples of scalars. (284) Distance, which is measured in metres, refers to how far an object has travelled during motion, whereas displacement (also measured in metres), refers to the change in position of an object in relation to direction and magnitude. Speed, which is measured in metres per second (m/s), describes the distance covered per unit time, whereas velocity (also measured in metres per second), describes the speed and direction of an object. Angular velocity which is measured in radians per second (rad/s) describes the time rate at which an object rotates about an axis. (285) Acceleration, which is measured in metres per second square (m/s^2), is defined as the rate of change of velocity, both in terms of speed and direction (286). Force (F), mass (m) and acceleration (a) are linked by Newton's second law, which states that 'the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass, and is expressed mathematically as F = ma. (286) Position and orientation are terms used to describe the placement of an object in space. The pose of a rigid object, which fully describes how it is placed in space, is determined by the combination of its position and orientation. (287) Cartesian co-ordinates (coordinate frames) are commonly used to describe the position of a point or rigid object in three-dimensional space using three mutually perpendicular vectors (the x-axis, y-axis, and z- axis). Translational movement along the x, y, and z axis is commonly referred to as surge, sway, and heave respectively. Orientation describes how an object is placed within the position it occupies, which is usually relative to a specified cartesian coordinate system of reference.

Pitch, roll, and yaw angles (also known as Tait-Bryan angles, nautical angles, or Cardan angles) describe the rotational orientation of an object relative to the vectors of a coordinate frame. (288) Euler angles, transformation matrices, and unit quaternions are other commonly used methods to mathematically describe the orientation of objects in three-dimensional space. (287)

6.1.1.1 Wired Electromagnetic tracking systems

Electromagnetic motion tracking systems calculate the relative position and orientation of sensors by changes in the magnetic flux detected from three orthogonal coils within a fixed electromagnetic field. (281) These systems have been proven to be highly accurate and reliable. (289) Accurate sensor pose estimation may be used in combination with time data to calculate velocity, jerk index (a measure of smoothness), and path length (distance travelled) metrics. Changes in the direction of acceleration may be used to calculate movement count. The use of electromagnetic motion tracking systems to objectively quantify surgical skill has been widely reported in simulated laboratory-based (62, 272, 273, 276, 290) and clinical studies. (291) Some of the major limitations of using of electromagnetic motion tracking systems in a clinical setting include: the relatively large size of the equipment; reliance on wires to connect sensors to the electromagnetic source; and potential inaccuracies in readings obtained when the sensors move towards the edge of the electromagnetic field. (281)

6.1.1.2 Wireless Inertial Measurement Unit (IMU) systems

Inertial measurement unit (IMU) sensors, or inertial sensors, are a type of microelectromechanical (MEM) system which are commonly used to capture motion data at high sampling rates. (292) Inertial sensors are not dependent on any external references or infrastructure, and typically comprise of three orthogonal accelerometers which measure translational acceleration in metres per second squared (m/s^2), and three orthogonal gyroscopes which measure rotational or angular velocity in radians per second (rad/s). (292, 293) Computer software allows the integration, or fusion, of data from these accelerometers and gyroscopes to calculate linear acceleration movement data. The major

advantages in using wireless IMU sensors in comparison to wired or optical motion tracking systems are that they are small, lightweight, discreet, unobtrusive, inexpensive, accurate, and can be positioned both securely and comfortably on the upper limbs for use in motion tracking in either laboratory or clinical settings. (57, 60, 280, 292, 294) A systematic review into the use of inertial sensors for human motion analysis concluded that inertial sensors may offer an accurate and reliable method to study human motion, but this is site and task specific. (281). Recent research has focused on using inertial sensor data for accurate position estimation, but the methodologies used are complex, experimental, and prone to inaccuracies. (292, 295) Data from inertial sensors may be used to generate movement counts using a threshold crossing technique. (296) This technique uses computer software in combination with accelerometery data to detect and count any spikes in acceleration over a specified threshold within the recorded time frame. The threshold crossing technique are utilised within this research to generate an objective quantitative metric of intentional hand movements (movement counts) performed by a surgeon during a set task. Fused tri-axial linear acceleration movement data from inertial sensors are acquired and analysed to determine these movement counts. Inertial sensor data is not used for determining pose estimation, path length (distance travelled), and jerk index (smoothness). This is because the initial pose of the inertial sensors is not recorded relative to a coordinate frame, and therefore sensor pose estimation, path length (distance travelled), and jerk index (smoothness) cannot be calculated. This limits the negative impact of the integration drift phenomenon, which is a recognised recording error when using inertial sensors, particularly in relation to position estimation over time. (292, 297) Interestingly, significant correlations between the total path-length derived from a validated arthroscopic simulator and the number of hand movements derived from elbow worn inertial sensors have been reported, indicating that this technique is sufficient to replace path length for determining task performance. (60)

6.2 Signal processing in wired and wireless motion analysis systems

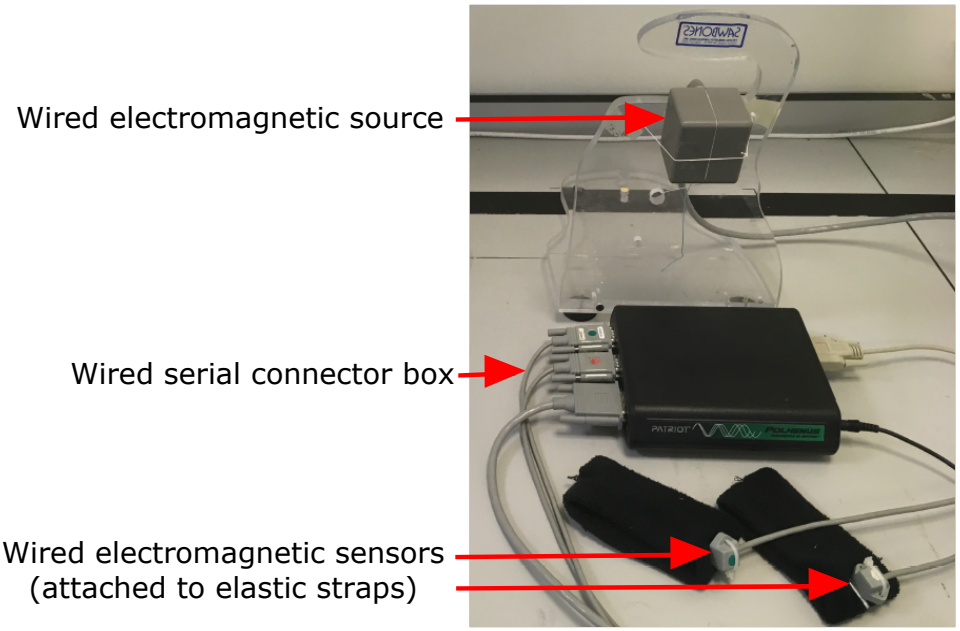
The wired electromagnetic and wireless IMU motion analysis systems are identical in all three linked validation studies. This section aims to outline the hardware, software, and data analysis protocols used for each system. The data used in the examples below are taken from an experiment in study A, which involved 30 repetitions of an arthroscopic probe along a simple uniplanar grid.

6.2.1 Wired electromagnetic tracking system hardware, data format, software, and signal processing

6.2.1.1 Hardware

The Patriot® system (Polhemus, Colchester, VT, USA) is a validated, low-cost, wired electromagnetic motion tracking system. (272, 276) This system collects pose estimation data of wired electromagnetic sensors to be collected at a sampling rate of 60Hz. The sensors measure the low-frequency magnetic field generated by the electromagnetic source within a range of 152cm (60 inches). (298) The sensors track the pose of the object to which they are attached, relative to the measurement reference frame. In this research two wired sensors are used, which are securely attached to elastic straps to facilitate placement on the hand and elbow. The wires of each sensor and the electromagnetic source attach to a serial connector box, and data is transferred from this box to a compatible computer using an RS-232 connector.

Figure 6-1: Patriot® electromagnetic motion tracking system hardware.



6.2.1.2 Software and data analysis

The Patriot® system uses the Polhemus PiMgr host user interface software to capture motion, which is installed and run-on Windows operating systems. A 2019 Dell OptiPlex 9020 3rd with a 3.5 GHz Intel® Core™ vPro processor running Windows 10 for data analysis (Dell Technologies., Austin, TX, USA) was used for data capture. The Patriot® system requires re-setting and both tracker and station re-configuration prior to each experiment. The trackers are configured to measure distance in centimetres, and the ordered data output parameters recorded are time (milliseconds); frame count; position (tri-axial Cartesian coordinate frame); and orientation (Euler angles). The data output list is formatted in the American National Standard Code for Information Interchange (ASCII), which defines an 8-bit code for display and control characters. Following data collection, a labelled text file (.txt) is exported for further analysis. Two custom scripts in MATLAB® (MathWorks, Inc., Natick, MA) are required for data processing. These were written and developed between 2009-2019 by Dr Stephen Mellon, Professor Richie Gill, and Dr Minsi Chen whilst working within NDORMS, University of Oxford.

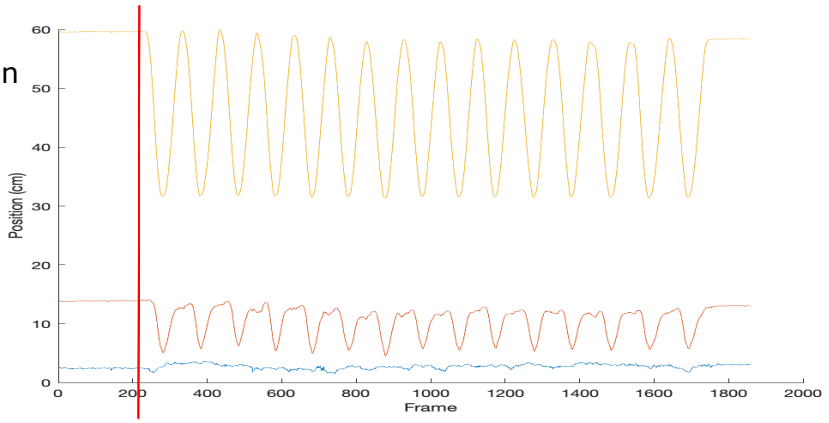
1) The first script takes the raw motion data output from the Patriot system and splits the position data by row for each sensor (labelled 1 and 2) according to the time stamp. The start point of the experiment and subsequent data analysis may be selected using a tool demonstrated by the red line in figure 6-2 below. The graphical representation of the sensor position remains steady prior to the start of each experiment because data recording commences approximately 5 seconds before participants are instructed to move.

Figure 6-2: **Steps for processing Patriot motion data in MATLAB®.**

STEP 1:
Patriot data input

Sensor	Time Stamp	Frame Count	X axis position	Y axis position	Z axis position	Pitch angle	Yaw angle	Roll angle
1	3C8DC	14663	0.457	1.136	10.639	160.131	-72.884	-43.992
2	3C8DC	14663	2.447	13.828	59.572	135.142	-69.591	-18.852
1	3C8EC	14664	0.452	-3.287	-23.072	160.052	-72.766	-43.907
2	3C8EC	14664	2.455	13.82	59.572	135.17	-69.594	-18.867
1	3C8FD	14665	0.626	-5.928	-43.835	160.142	-72.56	-43.959
2	3C8FD	14665	2.612	13.889	59.58	134.286	-69.739	-17.964
1	3C90E	14666	0.702	-7.59	-56.973	160.338	-72.509	-44.157
2	3C90E	14666	2.527	13.812	59.586	135	-69.668	-18.636
1	3C91E	14667	0.711	-8.879	-65.437	159.982	-72.376	-43.802
2	3C91E	14667	2.497	13.814	59.583	135.24	-69.629	-18.869

STEP 2:
MatLab data selection



STEP 3:
MatLab data output

Time	Sensor 1	X axis position	Y axis position	Z axis position	Sensor 2	X axis position	Y axis position	Z axis position
5.1	1	1.83	9.81	83.8	2	3.25	12.9	58.6
5.12	1	2.12	9.82	83.5	2	3.29	13.1	58.2
5.13	1	2.42	9.86	83.2	2	3.27	13	57.9
5.15	1	2.53	9.88	82.8	2	3.22	13.1	57.4
5.16	1	2.74	9.74	82.4	2	3.3	13.1	56.9
5.18	1	2.58	9.6	81.7	2	3.29	13.1	56.4
5.19	1	3.23	9.98	81.2	2	3.26	13.1	55.9
5.21	1	3.18	9.9	80.5	2	3.24	13.3	55.3
5.22	1	3.04	9.96	79.8	2	3.36	13.2	54.7
5.24	1	3.27	10.7	79	2	3.36	13.3	54

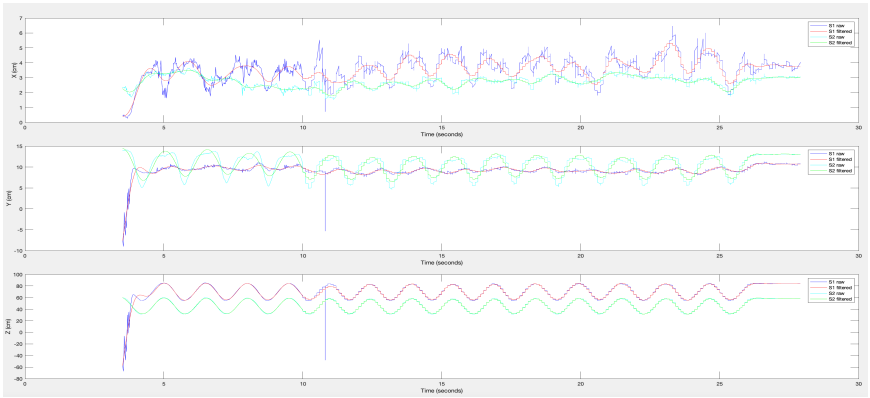
2) The second script, named ‘Manos’ (translation ‘hands’ in Spanish), uses the pre-processed motion data to calculate movement counts and path length. This script uses the combined positional and time stamp data to calculate the acceleration of each sensor and uses a threshold technique to determine movement counts. The threshold for generating a movement count was set at 10cm/s^2 (0.1m/s^2). The path length of each sensor is determined by using positional data to calculate the combined distance travelled within the tri-axial coordinate frame of the magnetic field.

Figure 6-3: **Steps for processing data using the Manos script in MATLAB®.**

STEP 1: MatLab data input

Time	Sensor 1	X axis position	Y axis position	Z axis position	Sensor 2	X axis position	Y axis position	Z axis position
5.1	1	1.83	9.81	83.8	2	3.25	12.9	58.6
5.12	1	2.12	9.82	83.5	2	3.29	13.1	58.2
5.13	1	2.42	9.86	83.2	2	3.27	13	57.9
5.15	1	2.53	9.88	82.8	2	3.22	13.1	57.4
5.16	1	2.74	9.74	82.4	2	3.3	13.1	56.9
5.18	1	2.58	9.6	81.7	2	3.29	13.1	56.4
5.19	1	3.23	9.98	81.2	2	3.26	13.1	55.9
5.21	1	3.18	9.9	80.5	2	3.24	13.3	55.3
5.22	1	3.04	9.96	79.8	2	3.36	13.2	54.7
5.24	1	3.27	10.7	79	2	3.36	13.3	54

STEP 2: MatLab data processing



STEP 3: MatLab data output

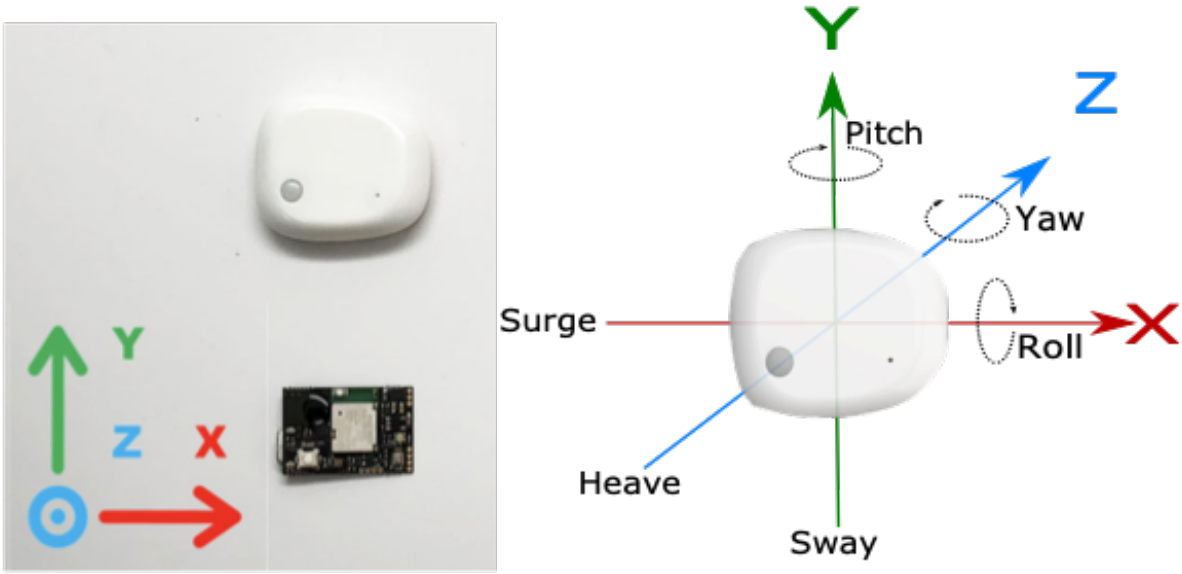
```
Time taken    27.900 seconds
Sample frequency  66.58 Hz, cut-off frequency   1.00 Hz
Sensor 1 total path travelled   926.563 cm
Sensor 2 total path travelled   812.921 cm
Threshold acceleration for movement set at  10.00 cm/s^2
Sensor 1 movements 323
Sensor 2 movements 349
```

6.2.2 Wireless Inertial Measurement Unit (IMU) hardware, data format, software, and signal processing

6.2.2.1 Hardware

MetaMotion R® (MMR®) inertial sensors (MBIENTLAB Inc., San Francisco, CA, USA) were used in the development of the novel wireless motion analysis system. These sensors were selected as they are small (36mmx27mmx10mm), contained within a splash resistant plastic case, lightweight (8 grams), affordable (US$ 100 per sensor), possess a rechargeable long battery life (up to 48 hours use per charge), and can be securely positioned on straps underneath sterile surgical gowns for use in a clinical environment. The use of MMR® inertial sensors for investigating human upper limb motion has been reported in several other recent research studies. (280, 294, 299)

Figure 6-4: **Metamotion R® Inertial Measurement Unit (IMU) sensor, case, coordinate frame axis, and movement references.**



6.2.2.2 Software and data analysis

The manufacturer of MMR® sensors provide an application programming interface (API) called MetaBase for streaming data wirelessly using Bluetooth Low Energy (BLE) technology directly onto compatible devices for further analysis. A 2019 3rd generation Apple® iPad Air, with a A12 Bionic processor running IOS 15.1 was used for data streaming, and a 2018 Apple® MacBook Pro 15', with a 2.6 GHz Intel® Core™ i7 processor running MacOS 12.0.1 was used for data analysis (Apple Inc., Cupertino, CA, USA). The MetaBase API also allows pairing of sensors, which facilitates the synchronisation of data acquisition for sensors positioned on two separate locations (for example right and left hands). Minimal variation in the sample rate of data acquisition has been reported between paired MMR® sensors when streaming data at 100Hz. (299) The small, low-power, 16-bit Bosch® BMI160 IMU sensors (Bosch, Gerlingen, Germany) within the MMR® can record tri-axial accelerometer, gyroscope, and geo-magnetometer data (total 9 axes) independently. The inbuilt Bosch® Sensortec fusion software BSX combines the measurements obtained from the accelerometer, gyroscope, and geomagnetic sensors alongside Kalman filtering technology to provide robust, distortion-free tri-axial linear acceleration data output. The inbuilt Kalman filtering function of these sensors reduces the background noise distortion, which is a recognised limitation in signal processing of data from inertial sensors. (300) The sensor fusion technology also benefits from gyroscopic drift cancellation, which is another recognised limitation of inertial sensors. (292) In this research the MMR® sensors were programmed to record tri-axial linear acceleration data in gravitational units against EPOCH timestamps at a sampling rate of 100Hz. This sampling rate is pre-determined when using the Bosch® Sensortec fusion software. In the laboratory experiments these data were recorded directly onto the 8MB in-built flash memory within the MMR® sensor, which can store approximately 15 minutes of continuously streamed data. Data is then transferred via BLE to a laptop in comma-separated values (.csv) format for analysis. Live streaming of data via BLE to a compatible device was used for the intra-operative recordings, as the data collection period exceeded the storage capacity of the sensors in-built flash memory. Analysis of inertial sensor data may be performed using either closed or open-source software. The benefits of using open-source software include transparency in data processing across research studies which may use different

inertial sensors. Most commercially available motion tracking systems use expensive closed-source software, which prohibit their use and interpretation of results generated. (301) This research investigates three independent signal processing techniques using the raw tri-axial linear acceleration data obtained from the MMR® sensors.

1) Movement counts generated through MATLAB® (MathWorks, Inc., Natick, MA) Signal Processing Toolbox™ and custom scripts.

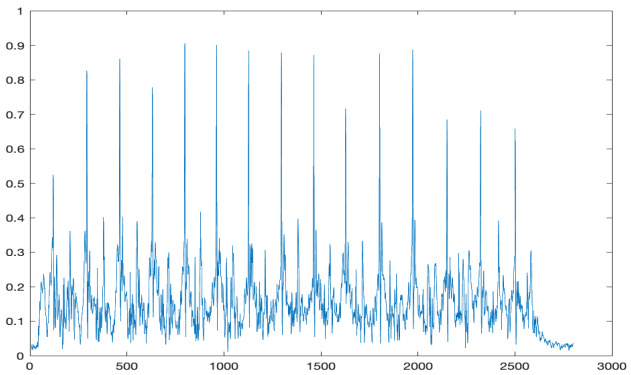
The custom scripts were developed by Dr Stephen Mellon, NDORMS using functions from the MATLAB® Signal Processing Toolbox™. (302, 303) The findpeaks function was used to identify and count the peaks in linear acceleration within the inertial sensor data. Raw tri-axial linear acceleration inertial sensor data in .csv file format is analysed using these scripts to produce movement counts per task or unit time specified. The linear acceleration data file, custom scripts, and timings file must be stored in the same computer folder to perform this analysis.

Figure 6-5: **Steps for processing IMU linear acceleration data in MATLAB®.**

STEP 1:
MMR data input

epoc (ms)	timestamp (+0000)	elapsed (s)	x-axis (g)	y-axis (g)	z-axis (g)
1575460000000	2019-12-04T11.19.33.979	3901.653	0	0.017	-0.026
1575460000000	2019-12-04T11.19.33.988	3901.662	0.002	0.015	-0.025
1575460000000	2019-12-04T11.19.33.998	3901.672	0.003	0.011	-0.028
1575460000000	2019-12-04T11.19.34.008	3901.682	0.008	0.009	-0.029
1575460000000	2019-12-04T11.19.34.019	3901.693	0.002	0.008	-0.03
1575460000000	2019-12-04T11.19.34.027	3901.701	0.001	0.008	-0.03
1575460000000	2019-12-04T11.19.34.038	3901.712	-0.001	0.01	-0.027
1575460000000	2019-12-04T11.19.34.048	3901.722	0.001	0.007	-0.024
1575460000000	2019-12-04T11.19.34.058	3901.732	0.001	0.009	-0.026
1575460000000	2019-12-04T11.19.34.068	3901.742	-0.005	0.005	-0.022

STEP 2:
MatLab data processing



STEP 3:
MatLab data output

ACTIVITY	START	STOP	DURATION	COUNT
A	00:00:00	00:03:00	00:03:00	483

2) Movement counts generated through the activityCounts package and custom scripts in RStudio (RStudio Team (2020): Integrated Development for R. RStudio, PBC, Boston, MA).

These scripts were developed by Dr Daniel Howgate, NDORMS using the open-source licence software package activityCounts. This package analyses raw tri-axial inertial sensor data presented in gravitational units to produce counts which significantly correlate with the movement counts generated by the widely used closed-source Actilife™ motion analysis software. (301) This package requires raw tri-axial linear acceleration inertial sensor data in .csv file format, which is loaded into RStudio global environment. The experiment start time is set, the sampling frequency of data in Hz is specified, and the data columns relating to the coordinate frame (x,y,z axes) are entered. The script is then run using these parameters, and the data output is movement count in each axis, which is summed to produce the total movement count.

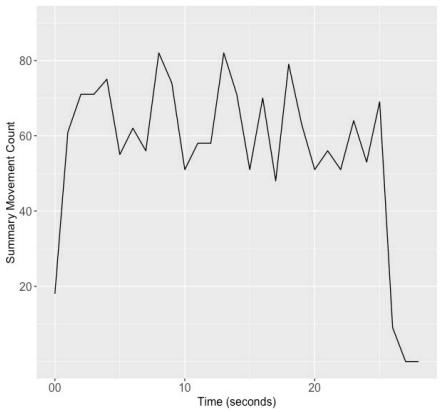
Figure 6-6: **Steps for processing IMU linear acceleration data in RStudio using activityCounts package.**

STEP 1:
MMR data input

epoc (ms)	timestamp (+0000)	elapsed (s)	x-axis (g)	y-axis (g)	z-axis (g)
1575460000000	2019-12-04T11.19.33.979	3901.653	0	0.017	-0.026
1575460000000	2019-12-04T11.19.33.988	3901.662	0.002	0.015	-0.025
1575460000000	2019-12-04T11.19.33.998	3901.672	0.003	0.011	-0.028
1575460000000	2019-12-04T11.19.34.008	3901.682	0.008	0.009	-0.029
1575460000000	2019-12-04T11.19.34.019	3901.693	0.002	0.008	-0.03
1575460000000	2019-12-04T11.19.34.027	3901.701	0.001	0.008	-0.03
1575460000000	2019-12-04T11.19.34.038	3901.712	-0.001	0.01	-0.027
1575460000000	2019-12-04T11.19.34.048	3901.722	0.001	0.007	-0.024
1575460000000	2019-12-04T11.19.34.058	3901.732	0.001	0.009	-0.026
1575460000000	2019-12-04T11.19.34.068	3901.742	-0.005	0.005	-0.022

STEP 2:
RStudio data processing using activityCounts

Time (seconds)	count x-axis	count y-axis	count z-axis	count sum
1	18	0	0	18
2	61	0	0	61
3	71	0	0	71
4	71	0	0	71
5	75	0	0	75
6	55	0	0	55
7	62	0	0	62
8	56	0	0	56
9	82	0	0	82
10	74	0	0	74
11	51	0	0	51
12	58	0	0	58
13	58	0	0	58
14	82	0	0	82
15	67	4	0	71
16	51	0	0	51
17	70	0	0	70
18	48	0	0	48
19	75	4	0	79
20	63	0	0	63
21	51	0	0	51
22	56	0	0	56
23	51	0	0	51
24	64	0	0	64
25	53	0	0	53
26	69	0	0	69
27	9	0	0	9
28	0	0	0	0
29	0	0	0	0



STEP 3:
RStudio data output

Summary Count	count x-axis	count y-axis	count z-axis
1609	1601	8	0

3) Movement counts and descriptive statistics of scalar magnitude of linear acceleration generated through the ggpmisc package and custom scripts RStudio (RStudio Team (2020): Integrated Development for R. RStudio, PBC, Boston, MA)

These scripts were developed by Dr Daniel Howgate, NDORMS using the open-source software package ggpmisc to analyse pre-processed inertial sensor data presented as the scalar magnitude of linear acceleration. (304) Pre-processing the raw tri-axial inertial sensor data using the root mean squared (RMS) technique produces a single scalar magnitude of linear acceleration (MLA) for each timestamp. Scalar MLA calculated using the RMS technique only provides information on sensor acceleration or deceleration, and not the direction of travel, path length, or pose estimation. The MLA may be used to calculate descriptive statistics during task performance and plotted using the ggmisc package in RStudio to determine peaks in the MLA when performing tasks. This allows threshold values in the MLA to be determined when performing specific actions in hip replacement, such as hammer blows for acetabular cup or femoral stem impaction. The RMS technique is easy to calculate and is well recognised in gait analysis research using inertial sensors. (305, 306) The MLA is defined as the square root of the sum of the squares of acceleration in each axis, and is expressed using the following formula:

$$MLA = \sqrt{(A_x^2 + A_y^2 + A_z^2)}$$

MLA = Magnitude of Linear Acceleration

A_x^2 = linear acceleration in x-axis

A_y^2 = linear acceleration in y-axis

A_z^2 = linear acceleration in z-axis

The ggpmisc package allows peaks and valleys in time series data to be located, tagged and plotted. (304) The stat_peaks function in this package allows thresholds in both timespan and amplitude of data to be set to define peaks. A peak is defined as “an element in a sequence which is greater than all other elements within a window of width span cantered at that element”. (304) A span value of 11 was used in this research, meaning that a peak is bigger than five consecutive numbers on either side. The linear acceleration data recorded by the MMR sensors is set at a frequency of 100Hz, and therefore 5 data frames equate to a timespan of 0.05 seconds. The ignore threshold below which peaks are ignored may be set between 0 - 1.0 relative to the maximum peak amplitude. This threshold was set to 0.05, which equates to the lowest 5% of peaks in linear acceleration being ignored. This function acts as a filter to remove the background movement noise in acceleration data.

Figure 6-7: Steps for processing IMU linear acceleration data in RStudio using ggpmisc package.

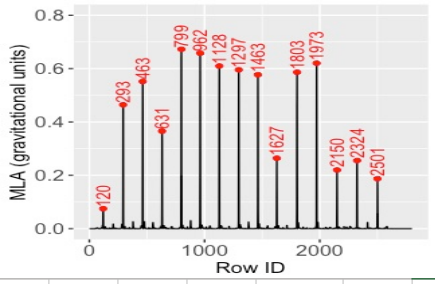
STEP 1:
MMR data input

epoc (ms)	timestamp (+0000)	elapsed (s)	x-axis (g)	y-axis (g)	z-axis (g)
1575460000000	2019-12-04T11.19.33.979	3901.653	0	0.017	-0.026
1575460000000	2019-12-04T11.19.33.988	3901.662	0.002	0.015	-0.025
1575460000000	2019-12-04T11.19.33.998	3901.672	0.003	0.011	-0.028
1575460000000	2019-12-04T11.19.34.008	3901.682	0.008	0.009	-0.029
1575460000000	2019-12-04T11.19.34.019	3901.693	0.002	0.008	-0.03
1575460000000	2019-12-04T11.19.34.027	3901.701	0.001	0.008	-0.03
1575460000000	2019-12-04T11.19.34.038	3901.712	-0.001	0.01	-0.027
1575460000000	2019-12-04T11.19.34.048	3901.722	0.001	0.007	-0.024
1575460000000	2019-12-04T11.19.34.058	3901.732	0.001	0.009	-0.026
1575460000000	2019-12-04T11.19.34.068	3901.742	-0.005	0.005	-0.022

STEP 2:
RStudio data pre-processing to calculate MLA

Row ID	epoc (ms)	timestamp (+0000)	elapsed (s)	x-axis (g)	y-axis (g)	z-axis (g)	SQRT x-axis (g)	SQRT y-axis (g)	SQRT z-axis (g)	Sum SQRT xyz	MLA
1	1575460000000	2019-12-04T11.19.33.979	3901.653	0	0.017	-0.026	0	0.000289	0.000676	0.000965	0.0000009312
2	1575460000000	2019-12-04T11.19.33.988	3901.662	0.002	0.015	-0.025	4.00E-06	0.000225	0.000625	0.000854	0.0000007293
3	1575460000000	2019-12-04T11.19.33.998	3901.672	0.003	0.011	-0.028	9.00E-06	0.000121	0.000784	0.000914	0.0000008354
4	1575460000000	2019-12-04T11.19.34.008	3901.682	0.008	0.009	-0.029	6.40E-05	8.10E-05	0.000841	0.000986	0.0000009722
5	1575460000000	2019-12-04T11.19.34.019	3901.693	0.002	0.008	-0.03	4.00E-06	6.40E-05	9.00E-04	0.000968	0.0000009370
6	1575460000000	2019-12-04T11.19.34.027	3901.701	0.001	0.008	-0.03	1.00E-06	6.40E-05	9.00E-04	0.000965	0.0000009312
7	1575460000000	2019-12-04T11.19.34.038	3901.712	-0.001	0.01	-0.027	1.00E-06	1.00E-04	0.000729	0.00083	0.0000006889
8	1575460000000	2019-12-04T11.19.34.048	3901.722	0.001	0.007	-0.024	1.00E-06	4.90E-05	0.000576	0.000626	0.0000003919
9	1575460000000	2019-12-04T11.19.34.058	3901.732	0.001	0.009	-0.026	1.00E-06	8.10E-05	0.000676	0.000758	0.0000005746
10	1575460000000	2019-12-04T11.19.34.068	3901.742	-0.005	0.005	-0.022	2.50E-05	2.50E-05	0.000484	0.000534	0.0000002852

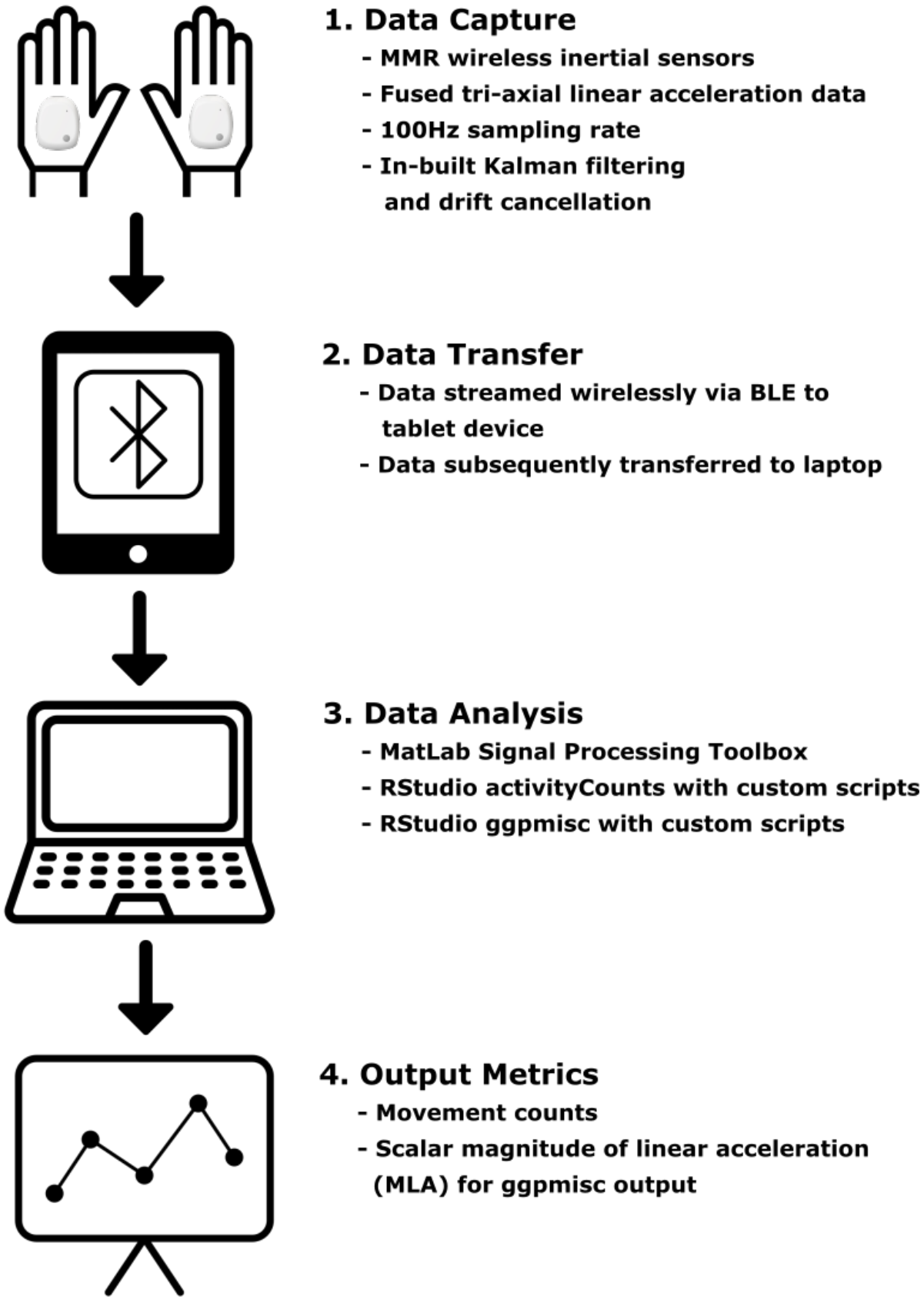
STEP 3:
RStudio plot MLA data and calculate descriptive statistics



Minimum	Q1	Median	Q3	Maximum	Mean	SD
0.00000	0.00009	0.00037	0.00143	0.67261	0.00664	0.04610

MLA	Row_ID
0.07485696	120
0.46437274	293
0.55182612	463
0.36557381	631
0.67261322	799
0.65802597	962
0.60983605	1128
0.59557182	1297
0.57709243	1463
0.26420422	1627
0.58657524	1803
0.62032006	1973
0.2199066	2150
0.25530182	2324
0.18712286	2501

Figure 6-8: Summary flowchart of wireless inertial sensor data capture and processing.



6.3 Study A: Content and concurrent validation of wired versus wireless systems for simple hand movements

6.3.1 Aims

The aims of this study are to:

1) Develop a laboratory model capable of simulating controlled simple hand movements.
2) Assess the content validity of wired and wireless motion analysis systems with paired sensors at the hand and elbow in determining the number of hand movements during simple tasks.
3) Assess the concurrent validity of a novel wireless motion analysis system against a validated wired motion tracking system when performing simple hand movement tasks.
4) Determine the magnitude of linear acceleration from wireless inertial sensors at the hand and elbow when performing simple tasks.

6.3.2 Methods

Ethical Approval

This study was conducted under ethical approval from the Medical Sciences Interdivisional Research Ethics Committee of the University of Oxford Central University Research Ethics Committee (CUREC) (MS-IDREC-R57808/RE001; Appendix D.1).

Participants

Three research staff from NDORMS (including the author) volunteered to participate in the data collection and simulated task performance in this study. Only two researchers were involved in any single experiment, with one assigned to perform the simulated task and the other assigned to data collection. All research staff were healthy right-hand dominant males.

Location

This study was conducted in the Oxford Orthopaedic Simulation and Education Centre (OOSEC), within NDORMS at the Nuffield Orthopaedic Centre.

Motion analysis systems and metrics

The two motion analysis systems used in this study were:

1) The Patriot® wired electromagnetic motion tracking system (Polhemus, Colchester, VT, USA). (272, 276) The hardware, software, and data analysis techniques used for this system have been described in section 6.2.1.

2) The novel wireless motion analysis system based upon MMR® inertial sensors. The hardware, software, and data analysis techniques used for this system have been described in section 6.2.2.

The primary outcome for these systems was the movement count generated. Descriptive statistics of the scalar MLA of inertial sensors for each task were secondary outcomes. The transfer and processing of the motion data for each system is outlined in section 6.2.

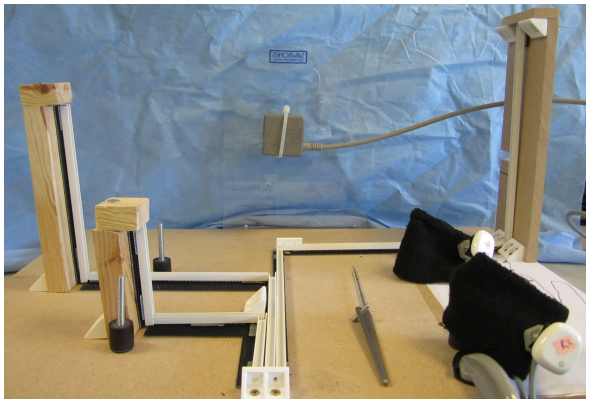
Simulated task set-up and protocol for data collection

A custom simulation rig was developed for assessing the number of simple hand movements in this study. This rig was designed to semi-constrain the direction and distance travelled for a set number of controlled participant hand movements. This rig contained a series of three triplanar grids. Three segments measuring 10, 20, and 30 cm were cut and used to construct three separate fixed-length three-dimensional grids within a single wooden baseplate clamped to a level worktop. These distances were selected as they are representative of the surgical field used during a primary total hip replacement, with the 10, 20, and 30 cm grids simulating small, medium, and large hand movements, respectively. The source of the wired electromagnetic motion tracking system was securely mounted onto a PVC stand and positioned adjacent to the wooden baseplate. All points of

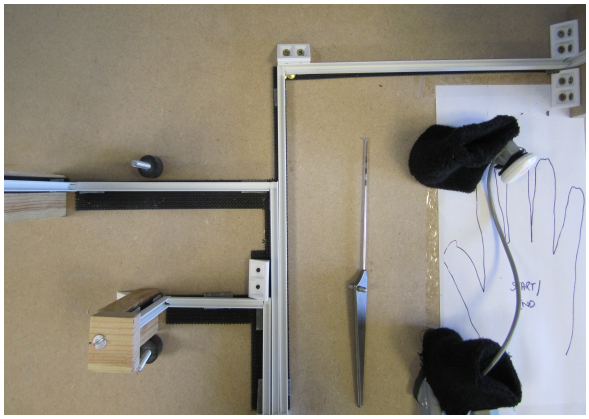
this simulation rig and electromagnetic sensors were contained within the recommended 152cm range of the source throughout the experiment. (298) Mobile phones and other large metal objects were positioned at least 3 metres away from the experimental field to prevent any potential interference with the electromagnetic motion tracking system.

Figure 6-9: **Custom rig used to simulate simple hand movements.**

Frontal view of simulation rig, arthroscopic probe, and paired sensors attached to black elastic straps



Aerial view of simulation rig, arthroscopic probe, and paired sensors attached to black elastic straps

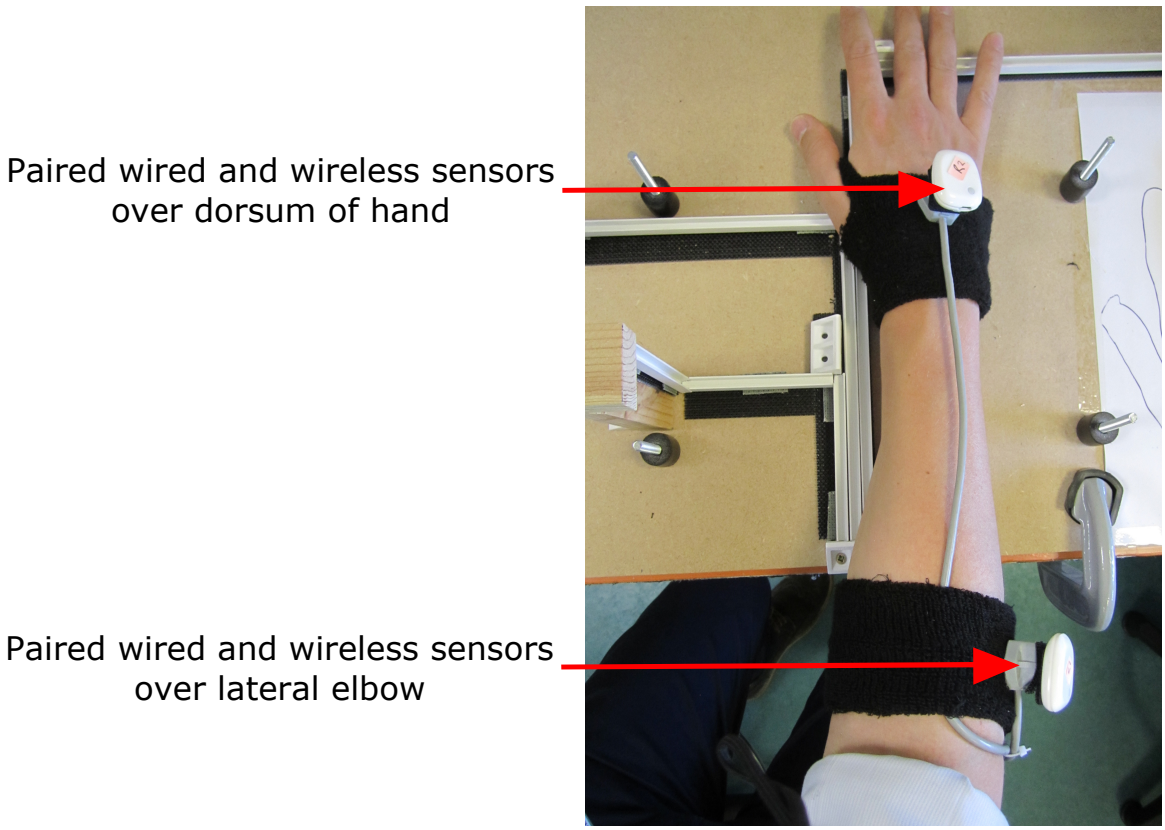


The wired electromagnetic sensors attached to elastic straps are then positioned over the participants dominant hand and elbow in the following positions:

1) **Hand**: Mid-point of the dorsum of the 3rd metacarpal
2) **Elbow**: 3cm distal to lateral epicondyle of distal humerus in line with the shaft of the radius

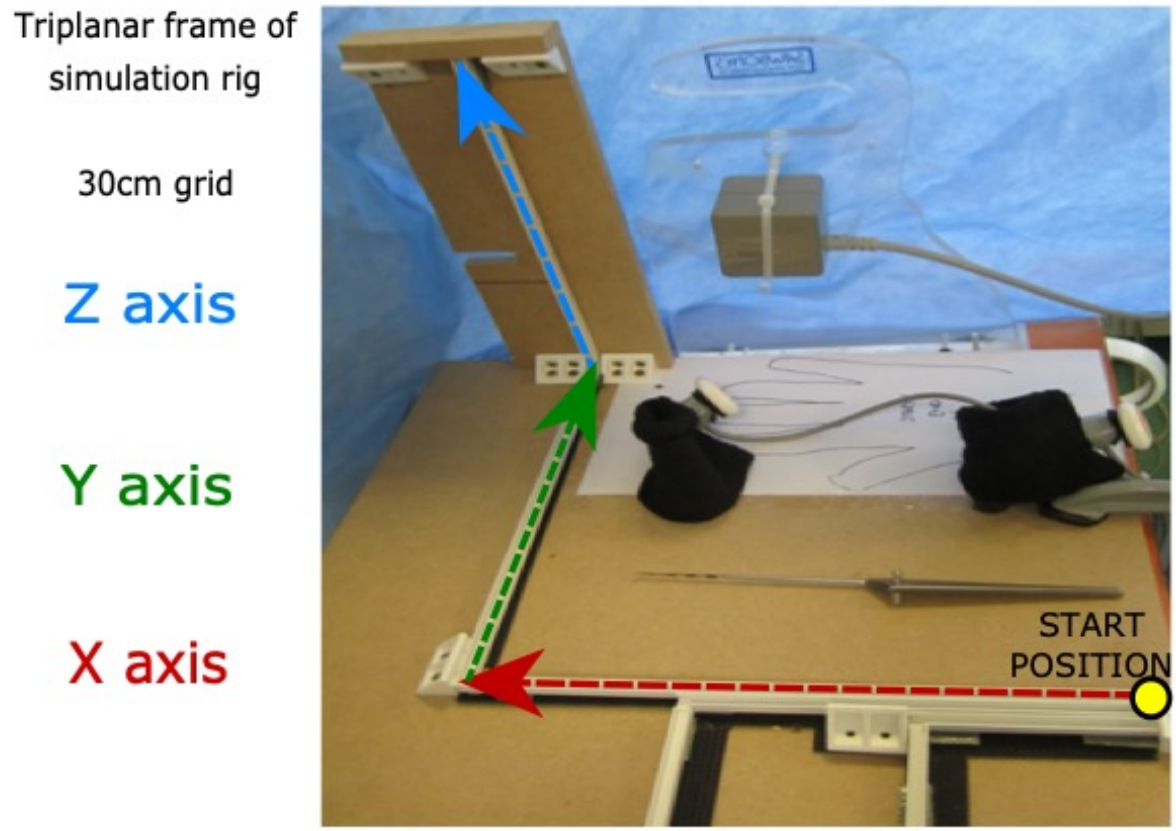
MMR® inertial sensors are securely attached directly on top of the electromagnetic sensors using adhesive Velcro tape. The validity of using elbow-worn inertial sensors for motion analysis and technical surgical skill has been demonstrated in previous laboratory (60) and clinical studies. (57) This set-up allows motion data to be captured from both the hand and elbow simultaneously using both wired and wireless systems. Following data analysis motion metrics may then be compared for both content and concurrent validation for between both systems.

Figure 6-10: **Positioning of paired wired and wireless sensors.**



The simple hand movement task requires a single participant to move an arthroscopic probe a pre-determined number of times (30, 60, 120, or 180 repetitions) along either the 10, 20, or 30cm grid, in either one, two, or three planes (uniplanar, biplanar, or triplanar). No prior experience or expertise was required for participants to perform these simple tasks. One actual hand movement count was defined as a passing of the arthroscopic probe completely along the length of a single plane of the grid. Uniplanar movements were performed on the x axis, biplanar movements on the xy axes, and triplanar movements on the xyz axes. For example, with the arthroscopic probe tip at the start position uniplanar movement tasks would require a total of two movements (x,x) to return the tip to the start position, whereas biplanar movements tasks would require a total of four movements (x,y,y,x), and triplanar movements tasks would require a total of six movements (x,y,z,z,y,x).

Figure 6-11: **Simulation rig demonstrating planes and start position of the probe.**



The task begins after the paired sensors have been positioned appropriately (figure 6-9) with the participant holding the arthroscopic probe still in their dominant right hand with the tip engaged at the start position (figure 6-11) within the groove of either the 10, 20, or 30cm grid. Data recording is then started simultaneously on both the wired and wireless systems, and once the recording status is confirmed, the participant executes the pre-determined number of movements within the grid. Once the task has been completed the participant was instructed to remain still until data recording was stopped on both systems.

Statistical analysis

Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The Pearson product moment correlation coefficient (PPMCC or Pearson's r) is used to determine the strength of any relationship between actual hand movement counts and those generated from the paired hand and elbow sensors in the wired and wireless motion analysis systems. Although no formal consensus exists for interpreting the strength of relationships based upon PPMCC, for the purposes of this research, any value <0.1 is considered a negligible correlation, 0.1 - 0.39 a weak correlation, 0.4 – 0.69 a moderate correlation, 0.7 – 0.89 a strong correlation, and >0.9 a very strong correlation. (240) Linear regression analysis is conducted on all significant relationships to determine the coefficient of determination (R^2) between observed movement counts and those generated by each motion analysis system. Bland-Altman (BA) plots and statistics is used to assess the level of agreement, and PPMCC is used to determine the strength of any relationship between movement counts generated by the validated wired Patriot® wired electromagnetic motion tracking system (Polhemus, Colchester, VT, USA) and the novel wireless motion analysis system. (307) Simple descriptive statistics are used to describe the MLA data obtained from the wireless motion analysis system. The significance threshold was set at 0.05 for all statistical analysis.

6.3.3 Results

A total of 63 simple hand movement motion analysis experiments were conducted using the bespoke simulation rig.

6.3.3.1 Content validation

Geometric jitter plots are used to represent the relationship between the movement counts generated from the paired sensors of the wired and wireless systems positioned at the hand and elbow (y axis) against actual movement counts performed for each experiment (x axis). Geometric jitter plots are better suited than scatterplots to visualise this data as they provide a small amount of random variation when plotting the fixed discrete value of the dependent variable (actual movement counts), to prevent overplotting of the independent variable value (measured movement counts). The jitter plots are faceted according to the plane of movement. Linear regression (R^2) and significance (p-values) for the experiments are printed in red within the faceted jitter plots. Summarised PPMCC, significance (p-values), and linear regression modelling outputs (intercept and beta coefficients) for each system and sensor position used across all 63 simple movement tasks are summarised in table 6-1.

Table 6-1: Summary of relationship and significance between measured and actual movement counts during simulated simple hand motion tasks.

Sensor Hardware	Connection	Position	Software	Signal processing Scripts	Pearson correlation coefficient	95% CI	p value	Linear regression intercept	Linear regression coefficient
Patriot	Wired	Hand	MATLAB®	Manos	0.95	0.92 - 0.97	< 2.2e-16	180.114	4.764
Patriot	Wired	Elbow	MATLAB®	Manos	0.96	0.93 - 0.97	< 2.2e-16	180.721	4.699
MMR	Wireless	Hand	MATLAB®	Signal Processing Toolbox	0.96	0.93 - 0.97	< 2.2e-16	170.08	20.07
MMR	Wireless	Elbow	MATLAB®	Signal Processing Toolbox	0.92	0.87 - 0.95	< 2.2e-16	267.07	12.58
MMR	Wireless	Hand	RStudio	activityCounts	0.69	0.54 - 0.8	3.12e-10	-467.86	45.01
MMR	Wireless	Elbow	RStudio	activityCounts	0.53	0.32 - 0.69	9.04e-06	-443.04	29.56

Figure 6-12: **Geometric jitter plots of movement counts generated by the wired motion tracking system against actual movement counts on the tri-planar simulation rig.**

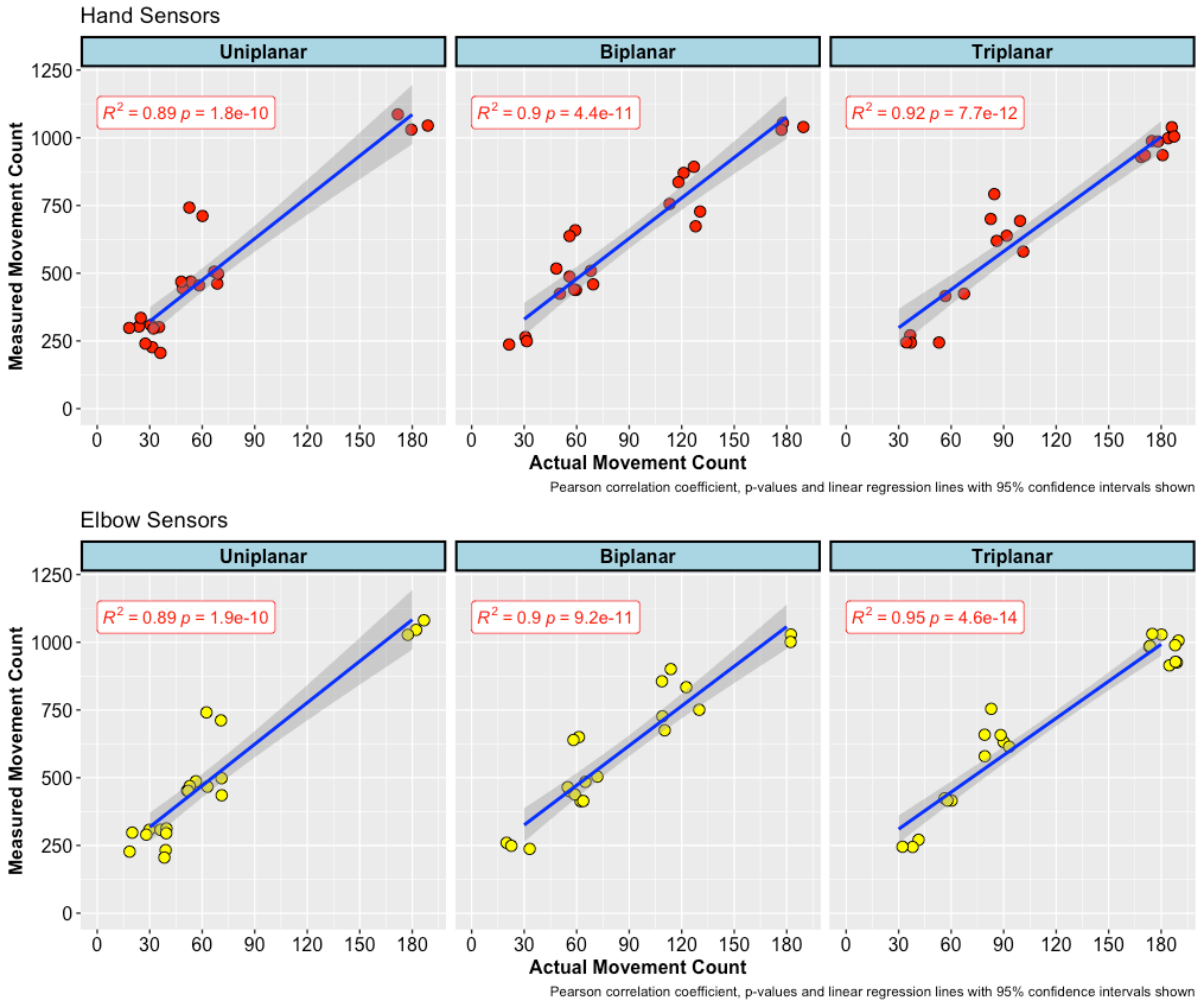


Figure 6-13: **Geometric jitter plots of movement counts generated by the wireless inertial sensors with MATLAB® Signal Processing against actual movement counts on the tri-planar simulation rig.**

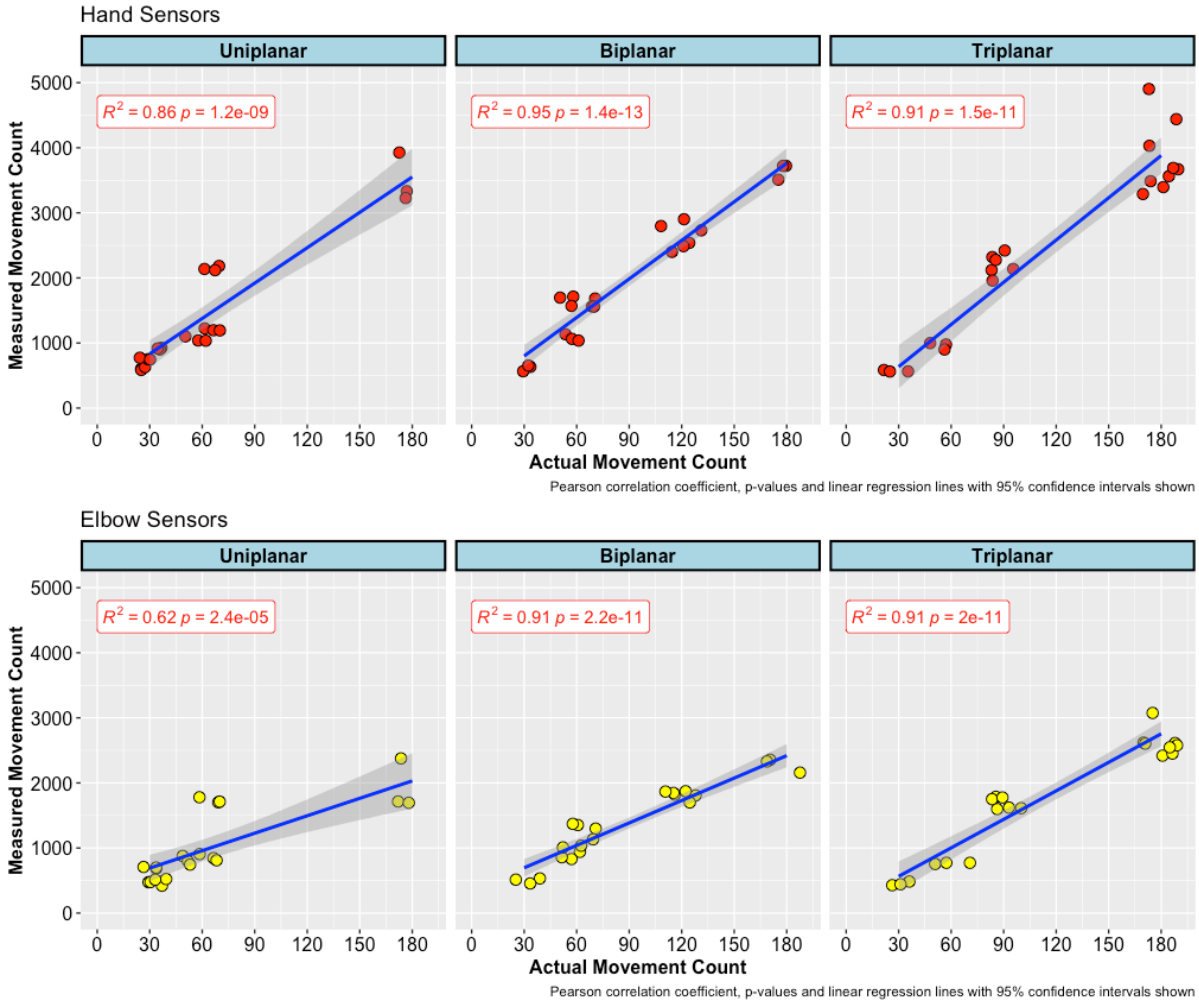
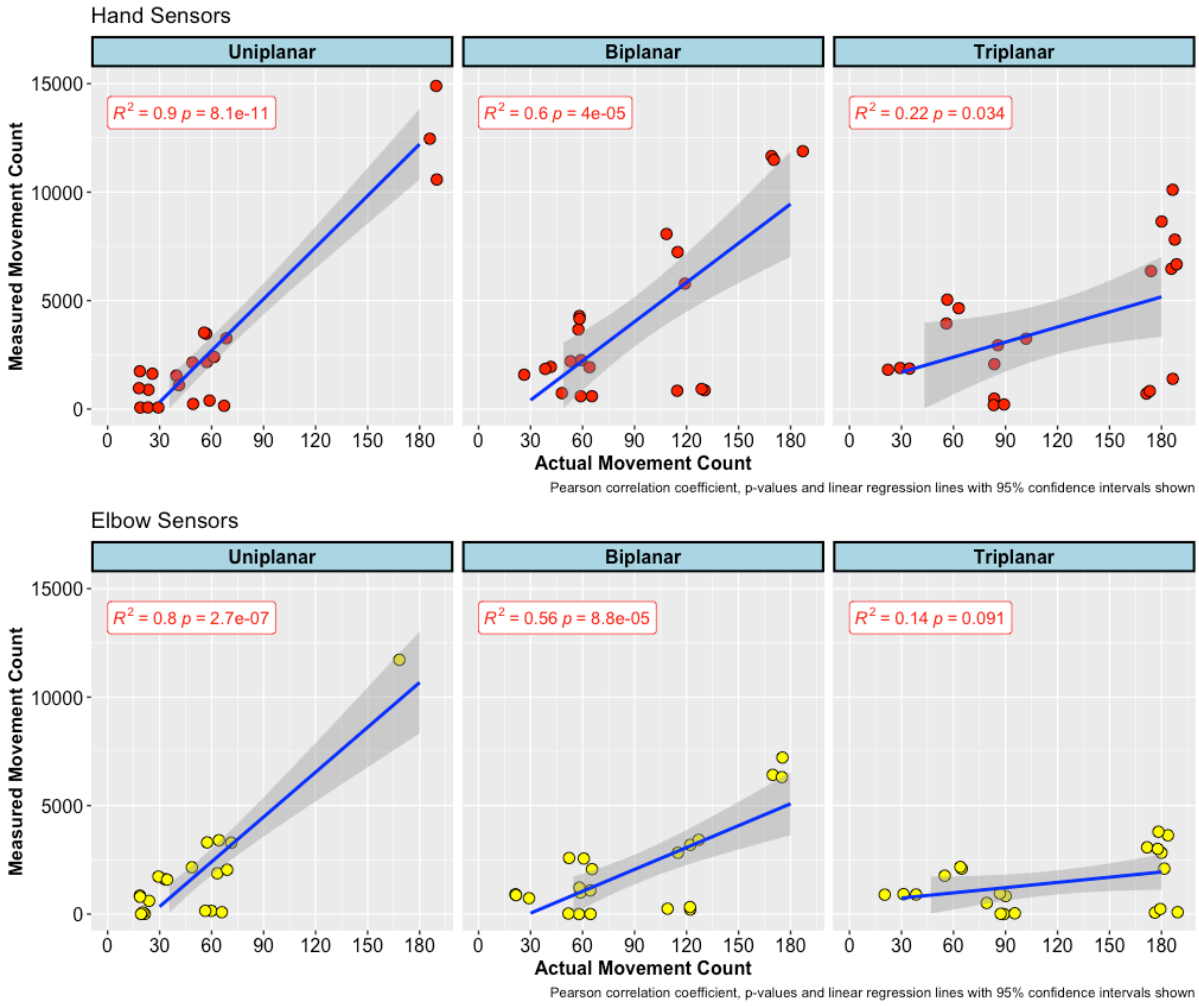


Figure 6-14: **Geometric jitter plots of movement counts generated by the wireless inertial sensors with RStudio activityCounts signal processing against actual movement counts on the tri-planar simulation rig.**



6.3.3.2 Concurrent validation

Bland-Altman plots and statistical analysis are used to visualise and assess the agreement between movement counts generated from the validated wired and novel wireless motion analysis systems for paired sensors positioned on the hand and elbow across all 63 simple movement tasks. Geometric jitter plots are used to represent the relationship between the movement counts generated by the wired (x axis) and wireless (y axis) systems for paired sensors positioned at the hand and elbow. Movement counts generated from both methods of signal processing for the wireless inertial sensor data (MATLAB® and activityCounts) are compared to those from the validated wired system. The jitter plots are again faceted according to the plane of movement. Significance (p-values) for the experiments on each grid size and plane of movement are printed in red within the faceted jitter plots. Summarised BA statistical analysis, PPMCC and significance (p-values) for the wired versus wireless movement counts generated across all 63 simple movement tasks are summarised in table 6-2.

Table 6-2: **Summary of relationship and significance between the movement counts generated by the wireless versus wired motion analysis systems during simulated simple hand motion tasks.**

Paired sensor position	Software	Signal processing Scripts	Pearson R	95% CI	p value	Mean difference	Lower limit	Upper limit	Critical difference
Hand	MatLab	Signal Processing Toolbox	0.93	0.88-0.95	< 2.2e-16	-1367.49	-3196.81	461.83	1829.32
Elbow	MatLab	Signal Processing Toolbox	0.88	0.81-0.93	< 2.2e-16	-795.78	-1870.87	279.311	1075.09
Hand	Rstudio	activityCounts	0.71	0.56-0.82	5.95e-11	-2974.02	-9815.44	3867.41	6841.42
Elbow	Rstudio	activityCounts	0.56	0.37-0.71	1.53e-06	-1613.6	-7561.55	4334.34	5947.94

Figure 6-15: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion tracking systems with MATLAB® Signal Processing.**

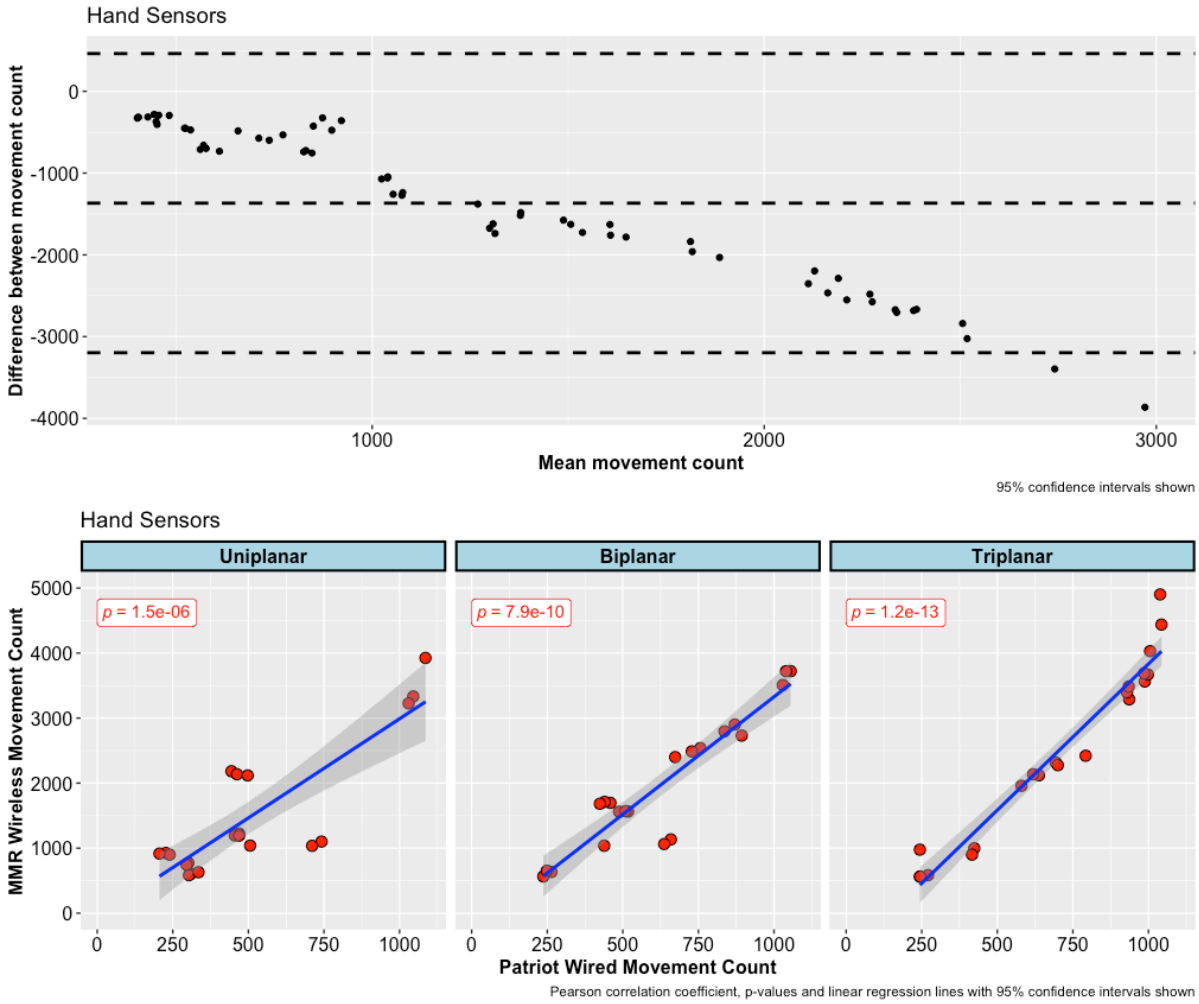


Figure 6-16: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion tracking systems with RStudio activityCounts signal processing.**

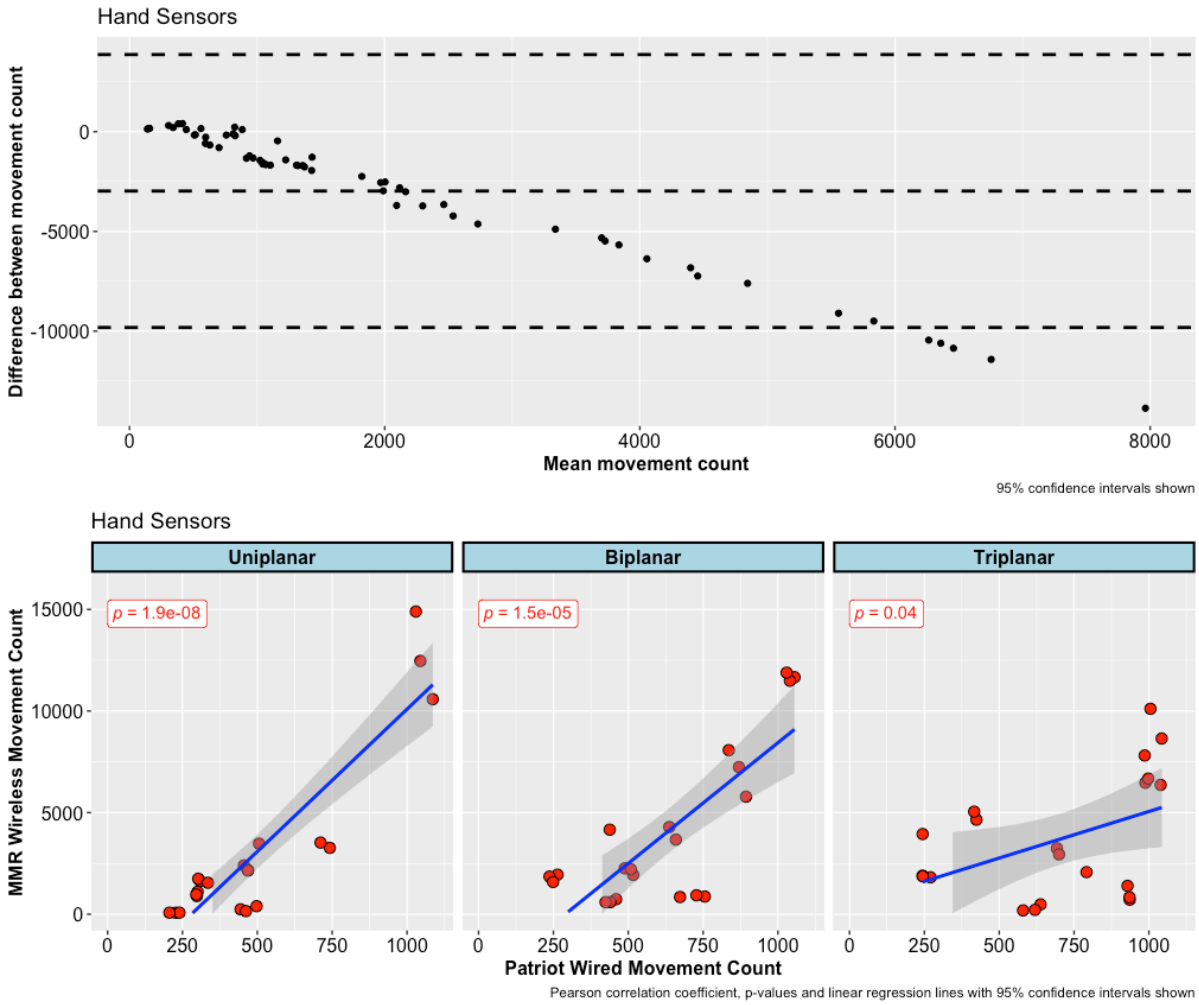


Figure 6-17: **Bland-Altman and scatter plots of movement counts generated by paired elbow sensors from the wired and wireless motion tracking systems with MATLAB® Signal Processing.**

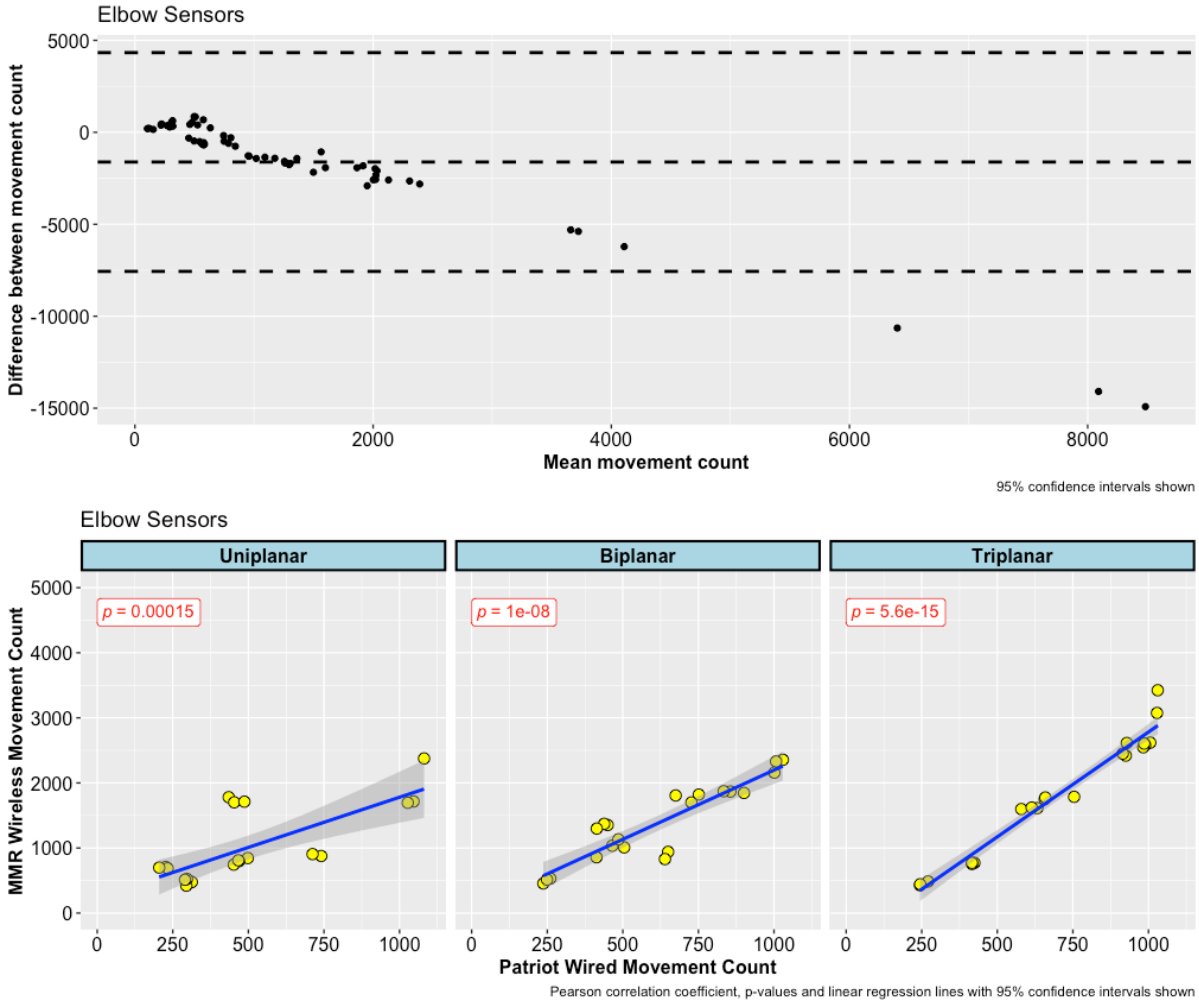
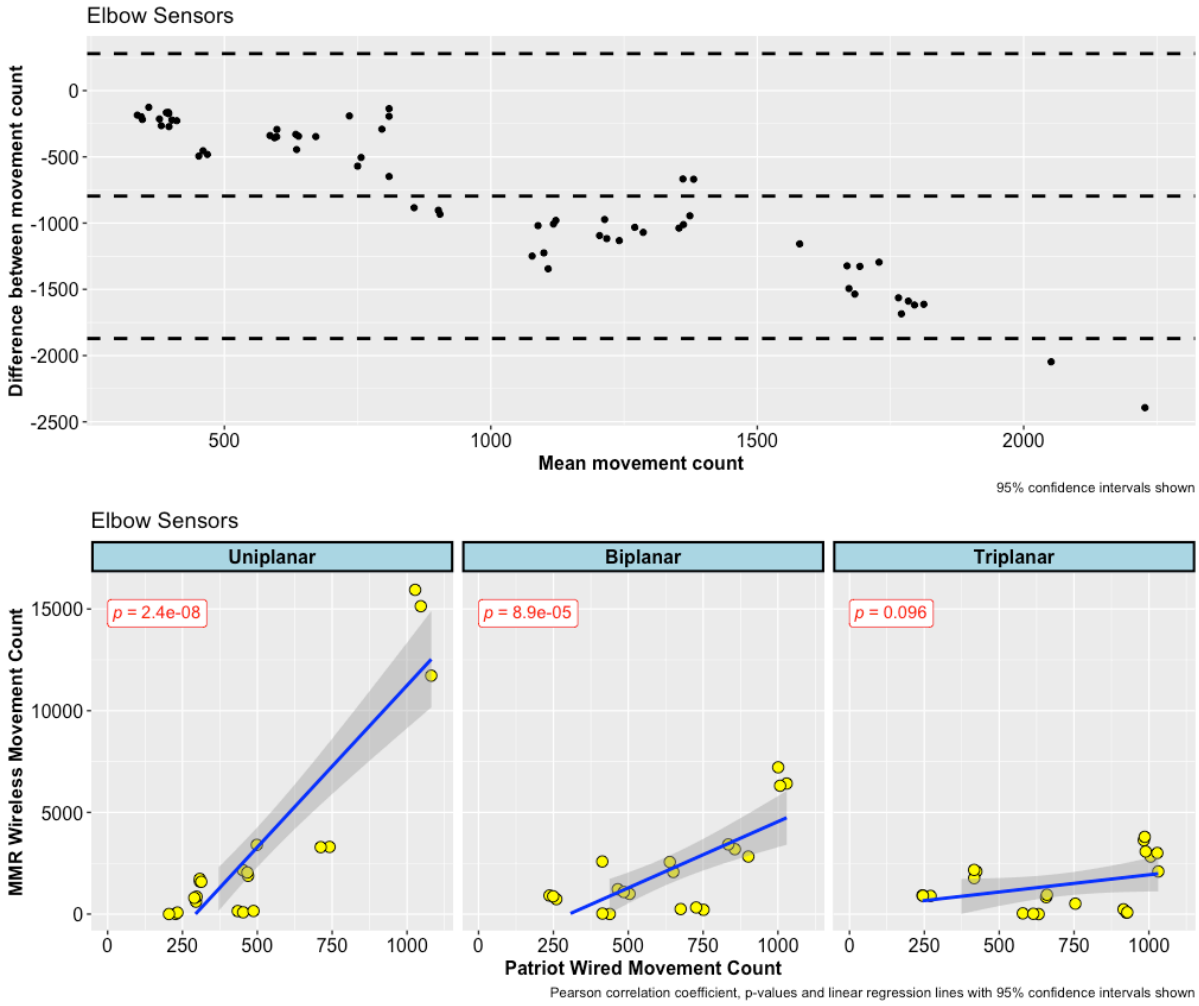


Figure 6-18: **Bland-Altman and scatter plots of movement counts generated by paired elbow sensors from the wired and wireless motion tracking systems with RStudio activityCounts signal processing.**



6.3.3.3 Scalar magnitude of linear acceleration during simple tasks

The scalar magnitude of linear acceleration (MLA) for the wireless inertial motion data was calculated for all 63 simple movement tasks experiments using the root mean squared (RMS) technique. The MLA may be analysed to determine the distribution of data, plotted to visualise the peaks during task performance, and generate descriptive statistics. Data analysis and visualisation from three individual experiments (D1/F1/H1) with paired wireless MMR inertial sensors at the hand and elbow are presented to highlight the differences in MLA during simple uniplanar (D1), biplanar (F1), and triplanar (H1) movements.

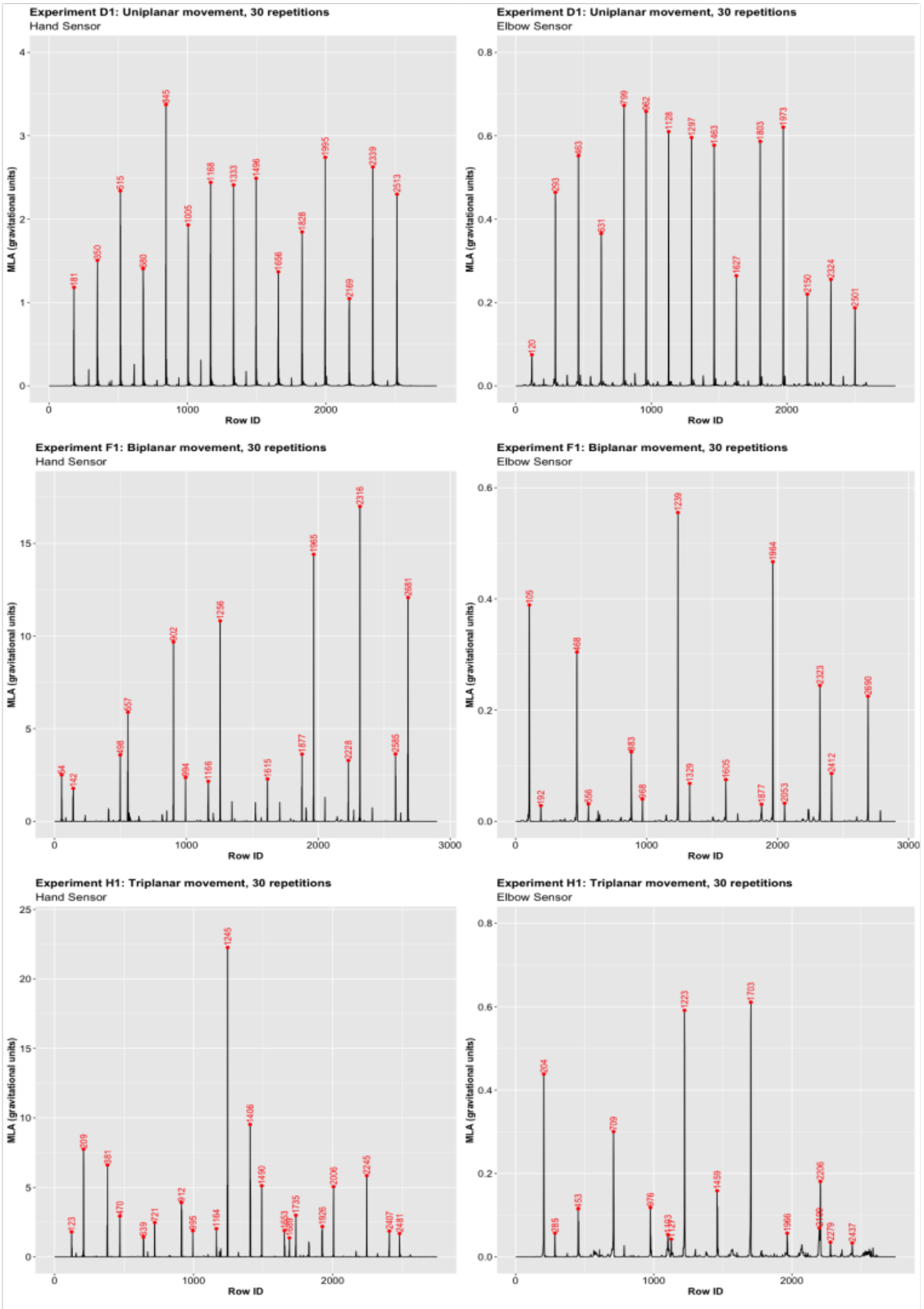
Distribution of MLA data

The Shapiro-Wilk test was used to determine the distribution of MLA data for each experiment. The p-value for both sensors (hand and elbow) for all experiments were all < 2.2e-16, indicating that the data were not normally distributed. Density plots indicated a positive skew to the data, with the mean average greater than the median average, and a long upper tail. Non-parametric statistical tests and the use of median and interquartile ranges are therefore justified for reporting descriptive statistics relating to the distribution of MLA data.

MLA data visualisation

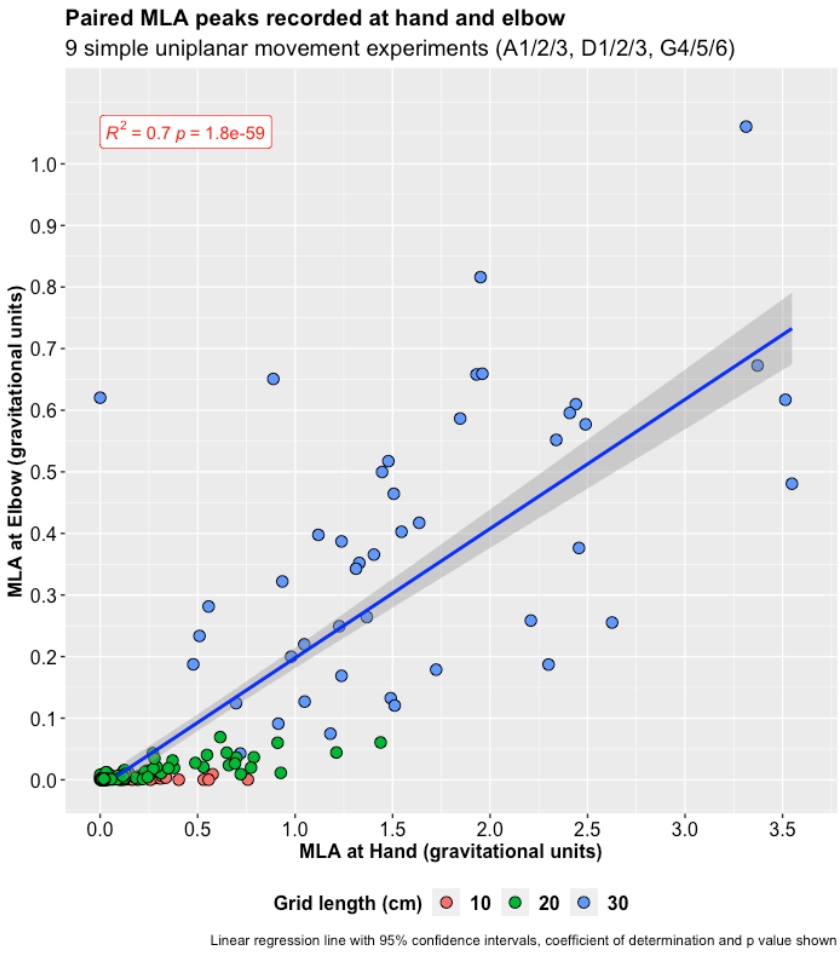
The ggpmisc package in RStudio was used to locate and tag peaks in MLA using the pre-defined timespan and amplitude parameters. (304) The MLA for both hand and elbow sensor data has been plotted in line graphs in figure 6-19.

Figure 6-19: **Line graphs of MLA from paired wireless inertial sensors positioned at the hand and elbow during simple uniplanar, biplanar, and triplanar movement tasks.**



These line graphs indicate that the peaks in MLA are the most consistent in amplitude and definition during uniplanar movements, as opposed to biplanar and triplanar movements. The peaks in MLA appear to correlate with rapid changes in the acceleration or direction of movement of the sensors, which typically occur when the tip of the arthroscopic probe abuts the end of the U-shaped plastic track on the simulation rig. At this point rapid deceleration of the sensors results in the visible peak in MLA. These peaks in MLA may be quantified from the paired sensors at the hand and elbow by tagging the row number (labelled in red on the line graphs) and extracting the finite MLA value from the data frame. The paired peaks in MLA recorded at the hand and elbow may then be visualised in a scatterplot, and both correlations and linear regression analysis performed to determine any relationship. The paired peaks in MLA from sensors at the hand and elbow for 9 simple uniplanar movement experiments using different length grids have been plotted in figure 6-20.

Figure 6-20: **Scatterplot demonstrating the relationship between peaks in MLA recorded by paired wireless inertial sensors positioned at the hand and elbow during simple uniplanar movements.**



The median MLA recorded during the simple uniplanar movement experiments was 0.12g (1.14m/s^2) for sensors positioned at the hand (IQR 0.54g), and 0.003g (0.03m/s^2) for sensors positioned at the elbow (IQR 0.03g), respectively. The maximum MLA recorded was 3.55g (34.8m/s^2) for sensors positioned at the hand, and 1.06g (10.4m/s^2) for sensors positioned at the elbow. This information may be used to determine thresholds for counting intentional movements during task performance for inertial sensors positioned at either the hand or elbow. The distribution of the paired MLA data is highlighted in table 6-3 below.

Table 6-3: **Summary of MLA (gravitational units) data distribution for paired hand and elbow sensors during simulated simple uniplanar movements.**

Sensor position	Minimum MLA	Q1 MLA	Median MLA	Q3 MLA	Maximum MLA	IQR
Hand	0.000025	0.02	0.12	0.56	3.55	0.54
Elbow	0.00007	0.001	0.003	0.03	1.06	0.03

The PPMCC between the paired hand and elbow peak MLA during these experiments is 0.84, 95% CI [0.79 - 0.87], $p<0.001$. The linear regression intercept for this relationship is 0.18, with a coefficient of 3.3. This strong linear relationship may therefore be used to estimate the MLA at the hand or elbow when either value is known.

6.4 Study B: Content and concurrent validation of wired versus wireless systems for task-specific hand movements in simulated THR

6.4.1 Aims

The aims of this study are to:

1) Develop laboratory models capable of simulating task-specific hand movements used when performing a primary THR.
2) Assess the content validity of wired and wireless motion analysis systems with paired sensors at the hand and elbow in determining the number of hand movements during task-specific movements.
3) Assess the concurrent validity of a novel wireless motion analysis system against a validated wired motion tracking system when performing task-specific hand movement tasks.
4) Determine the magnitude of linear acceleration from wireless inertial sensors at the hand and elbow when performing task-specific hand movements.

6.4.2 Methods

Unless otherwise specified the ethical approval, participants, location, motion analysis systems used, sensor positions, outcome measures, and statistical analysis methodology in this study are identical to those outlined in study A (section 6.3.2).

Simulated task set-up and protocol for data collection

To determine the face validity of movement counts generated by each motion analysis system (i.e., how representative they are for real life tasks) a series of simulated tasks requiring complex multiplanar hand movements were devised. These tasks focussed on specific movements and surgical activities required when performing a total hip replacement. The chosen tasks were:

1) Swinging a hammer.
2) Inserting a screw.
3) Suturing.

All simulated tasks were performed within the recommended 152cm range of the source of the wired electromagnetic motion tracking system throughout the experiment. (298) Mobile phones and other large metal objects were positioned at least 3 metres away from the experimental field to prevent any potential interference with the electromagnetic motion tracking system.

1) Simulated hammer swing

The action of swinging a hammer accurately is fundamental to the practice of orthopaedic surgery in general, and especially THR. Surgical hammers (also known as mallets) are instruments used for a variety of intra-operative tasks, most notably during the steps of femoral canal preparation when impacting broaches and rasps, uncemented femoral stem and acetabular cup impaction, and femoral head impaction. The upper limb biomechanics of swinging a hammer are complex and describing this action in detail is beyond the scope of this research. Although a wide range of techniques may be used by surgeons when swinging a hammer, most surgeons observed in this research use either a 'vertical' or 'oblique' plane of hammer swing intra-operatively. The 'vertical' hammer swinging motion uses a combination of explosive elbow extension and/or wrist ulnar deviation with the shoulder held in slight flexion and adduction. This action is commonly used in femoral broaching and prosthetic stem impaction. The 'oblique' hammer swinging motion uses a combination of explosive shoulder internal rotation and/or wrist ulnar deviation starting with the shoulder/humerus in an abducted and forward flexed position, and the elbow in fixed mid-flexion. This action is commonly used in acetabular cup impaction. An alternative 'horizontal' hammer swinging motion uses a combination of explosive shoulder internal rotation with the elbow held in mid flexion at the side of the body and the wrist joint in fixed neutral position. Visual examples of these hammer swings are contained within the intra-operative and simulation laboratory pictures in figure 6-21.

The simulation tasks and custom rig used in this study were designed to simulate the vertical, oblique, and horizontal movements described above. The vertical and horizontal hammer swinging tasks were performed using a femoral broach securely mounted onto an introducer handle (Taperfit™, Corin Group Ltd., The Corinium Centre, Cirencester, UK) and an adult male synthetic femur (Sawbones®, Pacific Research Laboratories, Vashon, WA, USA). The oblique hammer swinging task was performed using an uncemented acetabular cup securely mounted onto an introducer handle (Trinity™, Corin Group Ltd., The Corinium Centre, Cirencester, UK) and an adult male synthetic hemipelvis (Sawbones®, Pacific Research Laboratories, Vashon, WA, USA). The task begins after the paired sensors have been positioned appropriately (figure 6-10) with the participant holding the hammer still in their dominant right hand. Data recording is then started simultaneously on both the wired and wireless systems, and once the recording status is confirmed, the participant executes the pre-determined number of hammer swings. Following completion of the task the participant was instructed to remain still until data recording is stopped on both systems.

Figure 6-21: Pictorial representation of hammer swing planes.

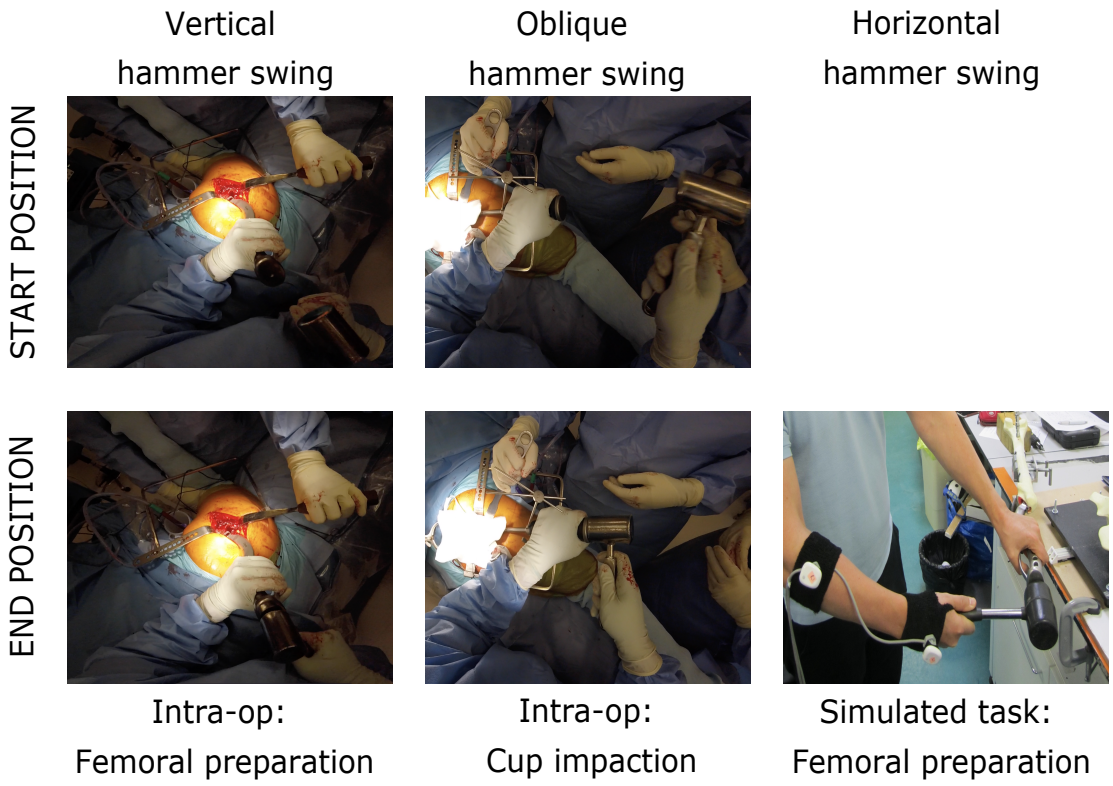
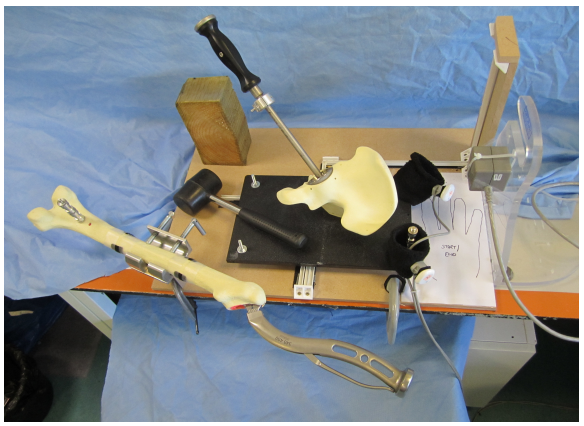
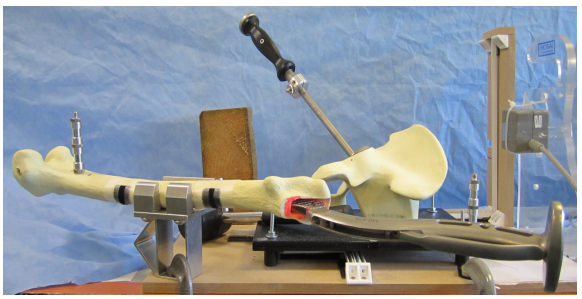


Figure 6-22: Custom rig used to simulate hand movements during hammer swings.

Aerial view of hammer swing simulation models, surgical equipment, and electromagnetic source.



Frontal view of hammer swing simulation models, surgical equipment, and electromagnetic source.



2) Screw insertion

The use of screws is ubiquitous in orthopaedic surgery. Total hip replacement is no exception, with screws commonly used to augment fixation in uncemented acetabular cups. Manually inserting a screw into any material involves repetitive rotational movements of the forearm (pro/supination). Although the total rotations about the central axis of a screw cannot easily be counted, the number of finite forearm rotational movements may. For the purposes of this study, four different lengths of 5mm thread diameter wood screws (16/20/30/40mm) were selected as they are representative of the diameter and lengths of screws used in THR. The task involved inserting a single screw into a pre-drilled track in a wooden block using a standard screwdriver (figure 6-23). The task begins after the paired sensors have been positioned appropriately with the participant holding the screwdriver in their dominant right hand with the head still and engaged in the screw head. Data recording is then started simultaneously on both the wired and wireless systems, and once the recording status is confirmed, the participant is instructed to insert the screw until the head is flush with the surface of the wood and cannot be advanced any further. The researcher responsible for data recording counts the number of forearm rotations required to fully insert the screw. The participant is instructed to remain still after the task has been completed and until data recording is stopped on both systems.

Figure 6-23: **Custom rig used to simulate hand movements during screw insertion.**

Frontal view of simulation rig for inserting wood screws



Aerial view of simulation rig for inserting wood screws



3) Simulated suturing

Suturing is a generic surgical skill, which requires bimanual technical dexterity and skill. Although many specialist suturing techniques have been described, the interrupted and continuous techniques remain the most common in contemporary surgical practice. The art of suturing requires very different types of hand movement compared to hammering and screw insertion. Co-ordinated, fluid, and fine movements from both hands are required for efficient suturing, with finite hand movements almost impossible to define by observation alone. For this reason, content validation of movement counts for each motion system is impracticable, and concurrent validation of movement counts obtained from the novel wireless motion analysis system in comparison to the validated wired system is investigated for both hands during the simulated suturing tasks.

The suturing task uses synthetic skin (Suture Tutor, Limbs & Things, Bristol, UK) and 3-0 ethylene terephthalate suture (Ethibond®, Ethicon Inc., Johnson & Johnson, Raritan, NJ, USA). The task begins after the paired sensors have been positioned appropriately with the participant holding the suture secured in a needle holder in their dominant right hand and forceps in their left hand. Data recording is then started simultaneously on both the wired and wireless systems, and once the recording status is confirmed, the participant is instructed to complete a series of either 5 interrupted sutures, or 5 continuous sutures with the knots tied at the beginning and end. The participant is instructed to remain still after the task has been completed and until data recording is stopped on both systems.

Figure 6-24: **Custom rig used to simulate hand movements during suturing.**

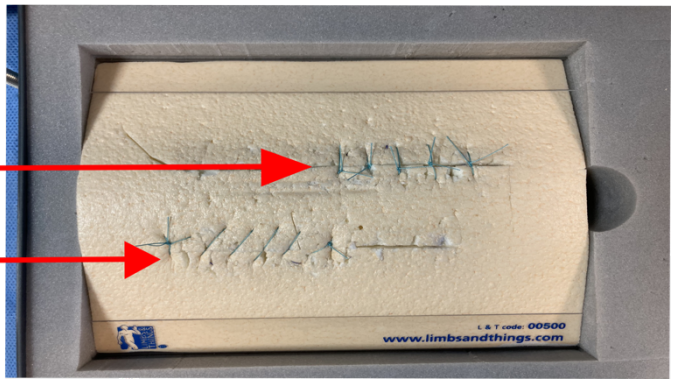
Frontal view of simulation rig for suturing, surgical equipment and electromagnetic source



Aerial view of simulation rig for suturing with examples of:

Interrupted sutures

Continuous sutures



6.4.3 Results

A total of 57 complex multiplanar hand movement motion analysis experiments were conducted using the bespoke simulation models.

6.4.3.1 Content validation

The content validity of both wired and wireless motion analysis systems is investigated for simulated hammer swings and screw insertion, as the actual observed movement counts performed by participants during these tasks may be counted. One actual hand movement count was defined as one swing of the hammer (impaction on introducer handle), or one forearm rotation during screw insertion. Scatterplots are used to represent the relationship between the movement counts generated from the paired sensors of the wired and wireless systems positioned at the hand and elbow (y axis) against actual movement counts performed for each experiment (x axis). The scatterplots are faceted according to the sensor position and the plane of movement for hammer swings. Linear regression (R^2) and significance (p-values) for the experiments on each grid size and plane of movement are printed in red within the faceted scatterplots. Summarised PPMCC, significance (p-values), and linear regression modelling outputs (intercept and beta coefficients) for each system and sensor position used within the simulated hammer swing and screw insertion experiments are summarised in table 6-4.

Regards the simulated hammer swing experiments, strong and statistically significant correlations between actual and measured movement counts were observed using sensors positioned at the hand from the wired Patriot system (PPMCC = 0.81, 95% CI [0.54, 0.92], p=5.55e-5), followed closely by the wireless sensors with activityCounts signal processing (0.8, 95% CI [0.53, 0.92], p=7.24e-5), and finally the wireless sensors with MATLAB® signal processing toolbox (0.78, 95% CI [0.5, 0.91], p=0.000126). Interestingly, the strongest correlations between actual and measured hammer swings from sensors positioned at the elbow during these experiments were obtained using the activityCounts signal processing package (0.77, 95% CI [0.48, 0.91], p=1.66e-4), followed closely

by the wireless sensors with MATLAB® signal processing toolbox (0.73, 95% CI [0.4, 0.89], p=0.00057). Only moderate correlations were observed during the simulated hammer swing experiments using sensors from the wired Patriot system positioned at the elbow (0.48, 95% CI [0.02, 0.77], p=0.04).

Regards the simulated screw insertion experiments, strong and statistically significant correlations between actual and measured movement counts were observed using sensors positioned at the hand from the wired Patriot system (PPMCC = 0.92, 95% CI [0.76, 0.97], p=1.42e-6), followed closely by the wireless sensors with MATLAB® signal processing toolbox (0.87, 95% CI [0.66, 0.96], p=2.02e-5). Only moderate and statistically insignificant correlations were observed during the simulated screw insertion experiments using wireless sensors with activityCounts signal processing (0.48, 95% CI [-0.05, 0.79], p=0.07). Interestingly, for sensors positioned at the elbow during the simulated screw insertion experiments, only the wireless sensors with MATLAB® signal processing toolbox demonstrated strong and statistically significant correlations between actual and measured movement counts (0.74, 95% CI [0.37, 0.91], p=0.0015).

Table 6-4: Summary of relationship and significance between measured and actual movement counts during simulated hammering and screw insertion.

Task	Sensor Hardware	Connection	Position	Software	Signal processing Scripts	Pearson R	95% CI	p value	Linear regression intercept	Linear regression coefficient
Hammering	Patriot	Wired	Hand	MatLab	Manos	0.81	0.54-0.92	5.55E-05	15.56	10.79
Hammering	Patriot	Wired	Elbow	MatLab	Manos	0.48	0.02-0.77	0.04368	45	4.7
Hammering	MMR	Wireless	Hand	MatLab	Signal Processing Toolbox	0.78	0.5-0.91	0.000126	62.56	12.74
Hammering	MMR	Wireless	Elbow	MatLab	Signal Processing Toolbox	0.73	0.4-0.89	0.00057	108.78	9.33
Hammering	MMR	Wireless	Hand	Rstudio	activityCounts	0.8	0.53-0.92	7.24E-05	44.11	342.47
Hammering	MMR	Wireless	Elbow	Rstudio	activityCounts	0.77	0.48-0.91	1.66E-04	-409.7	116.3
Screw insertion	Patriot	Wired	Hand	MatLab	Manos	0.92	0.76-0.97	1.42E-06	6.38	8.85
Screw insertion	Patriot	Wired	Elbow	MatLab	Manos	0.33	-0.21-0.72	0.22	69	2.42
Screw insertion	MMR	Wireless	Hand	MatLab	Signal Processing Toolbox	0.87	0.66-0.96	2.02E-05	109.31	12.94
Screw insertion	MMR	Wireless	Elbow	MatLab	Signal Processing Toolbox	0.74	0.37-0.91	0.001504	180.29	7.9
Screw insertion	MMR	Wireless	Hand	Rstudio	activityCounts	0.48	-0.05 - 0.79	7.00E-02	2716	97.8
Screw insertion	MMR	Wireless	Elbow	Rstudio	activityCounts	-0.12	-0.59-0.42	6.80E-01	244.42	-2.01

Figure 6-25: **Scatterplots of movement counts generated by the wired motion tracking system against actual movement counts during simulated hammer strikes and screw insertion.**

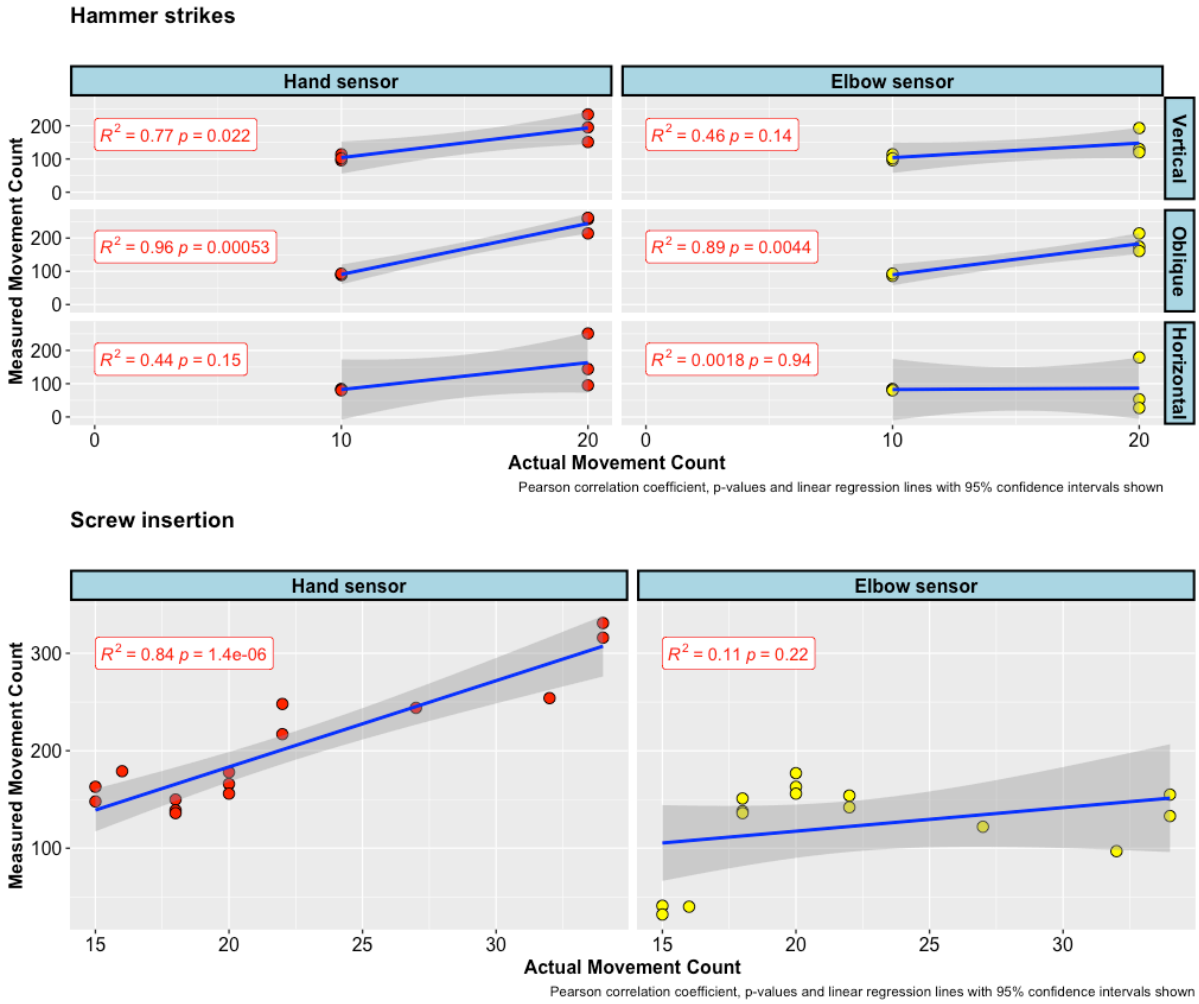


Figure 6-26: **Scatterplots of movement counts generated by the wireless inertial sensors with MATLAB® Signal Processing against actual movement counts during simulated hammer strikes and screw insertion.**

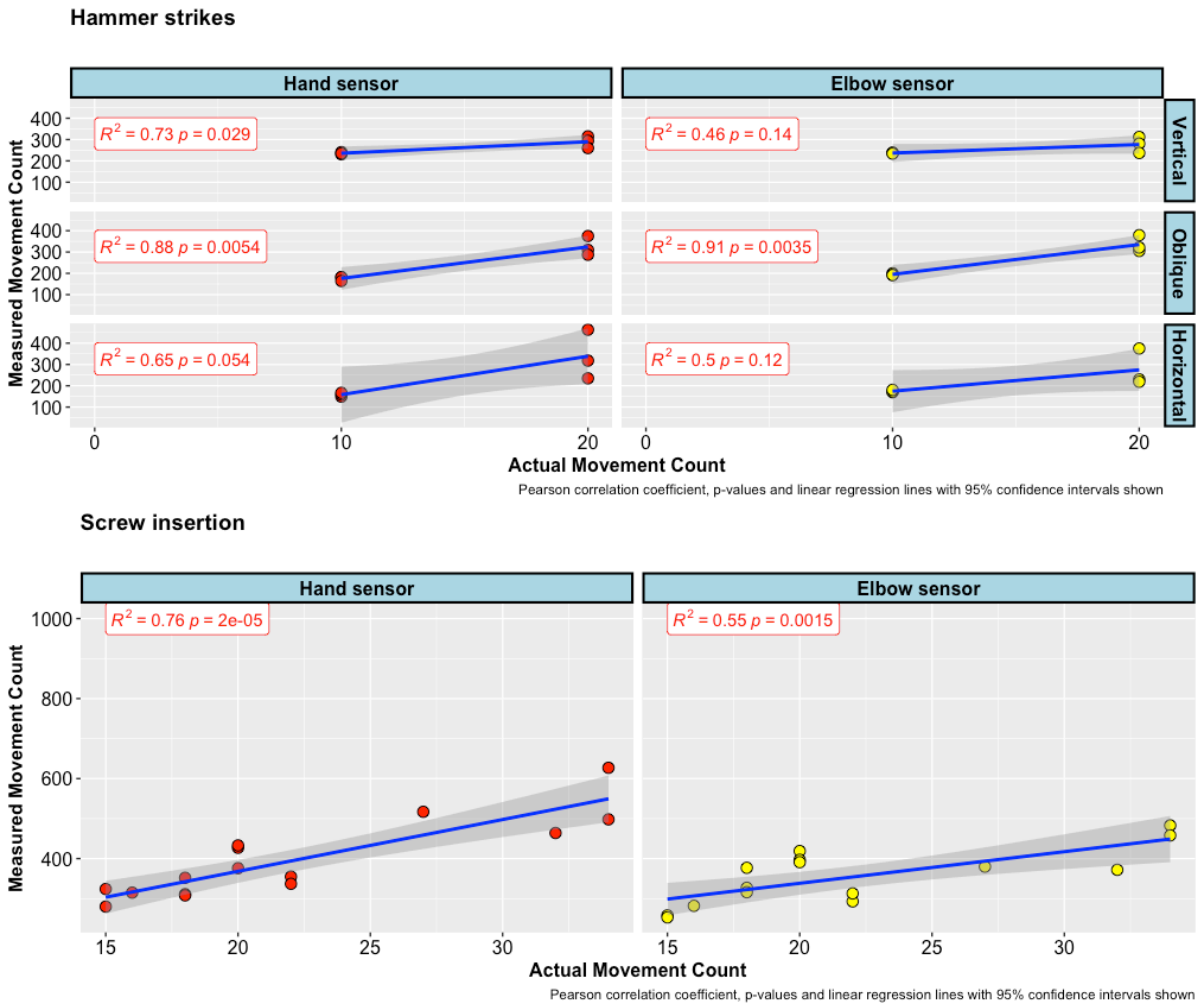
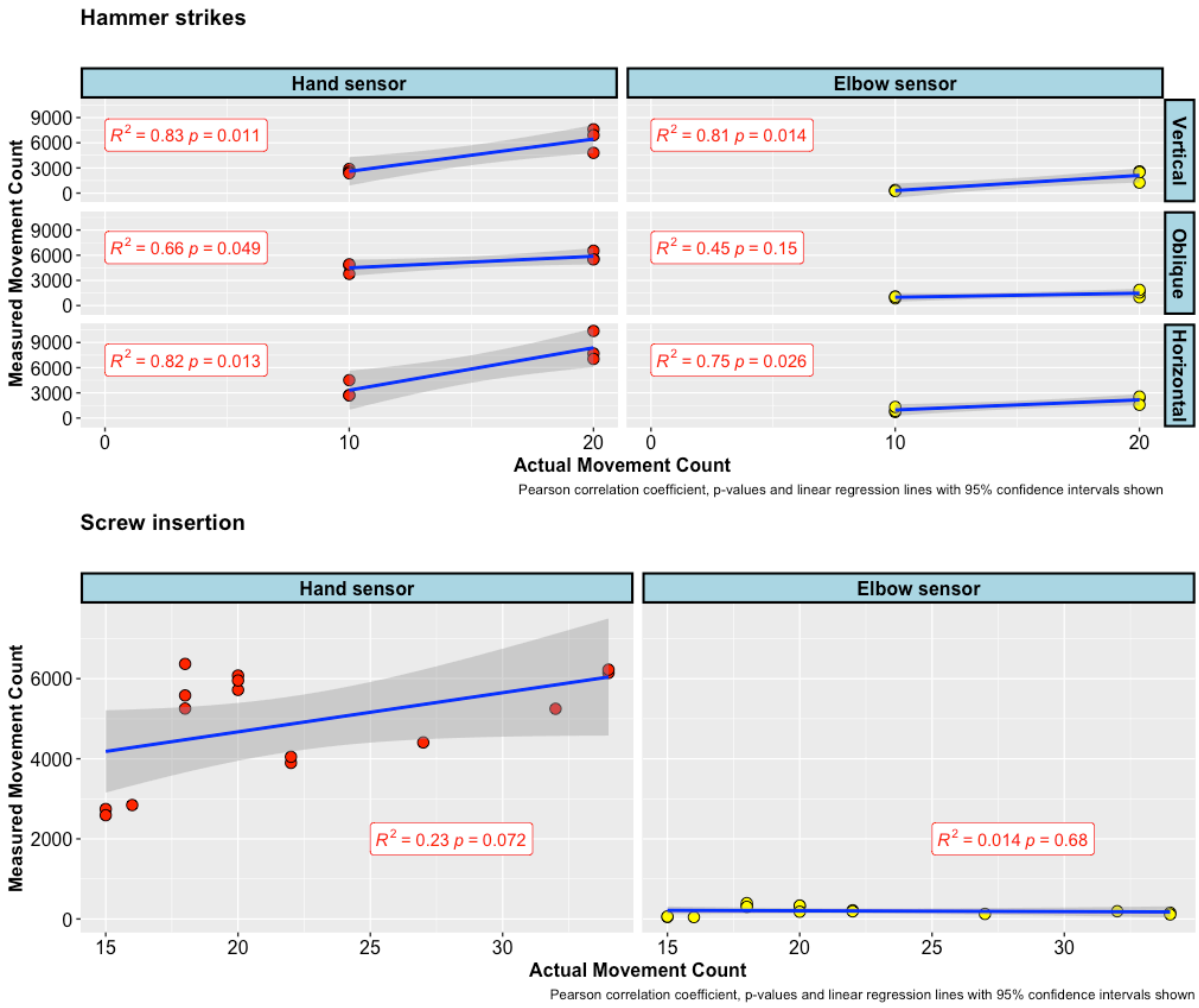


Figure 6-27: **Scatterplots of movement counts generated by the wireless inertial sensors with RStudio activityCounts signal processing against actual movement counts during simulated hammer strikes and screw insertion.**



6.4.3.2 Concurrent validation

Bland Altman plots and statistical analysis are used to visualise and assess the agreement between movement counts generated from the validated wired and novel wireless motion analysis systems for paired sensors positioned on the hand and elbow across all 57 complex movement tasks. Scatterplots are used to represent the relationship between the movement counts generated by the wired (x axis) and wireless (y axis) systems for paired sensors positioned at the hand for each task, and for elbow sensors during the simulated hammer swinging exercises. Results from the content validation studies in section 6.4.3.1 have demonstrated that correlations between actual and measured movement counts during simulated screw insertion were only observed using the wireless sensors with MATLAB® signal processing toolbox. Therefore, further concurrent validation analysis between the wired and wireless motion analysis systems for sensors positioned at the elbow is not necessary. Movement counts generated from both methods of signal processing for the wireless inertial sensor data (MATLAB® and activityCounts) is compared to those from the validated wired system. The scatterplots are faceted according to the plane of hammer swinging movement, or suturing technique. Significance (p-values) for the experiments on each grid size and plane of movement are printed in red within the faceted scatterplots. Summarised BA statistical analysis, PPMCC and significance (p-values) for the wired versus wireless movement counts generated across all 57 complex movement tasks are summarised in table 6-7.

Regards the simulated hammer swing experiments, moderate and statistically significant correlations in movement counts generated from sensors positioned at the hand were observed between the wired Patriot system and the wireless sensors using both activityCounts signal processing (PPMCC = 0.64, 95% CI [0.25, 0.85], p=0.0039) and MATLAB® signal processing toolbox (0.59, 95% CI [0.17, 0.83], p=0.0097). Only weak and statistically insignificant correlations in movement counts generated from sensors positioned at the elbow were observed between the wired Patriot system and wireless sensors using the MATLAB® signal processing toolbox (0.38, 95% CI [-0.11, 0.72], p=0.12) or activityCounts signal processing package (PPMCC = 0.29, 95% CI [-0.2, 0.67], p=0.237).

Regards the simulated screw insertion experiments, strong and statistically significant correlations in movement counts generated from sensors positioned at the hand were observed between the wired Patriot system and the wireless system using the MATLAB® signal processing toolbox (PPMCC = 0.78, 95% CI [0.46, 0.93], p=5.32e-4), but weak and statistically insignificant correlations when using activityCounts signal processing (0.2, 95% CI [-0.35, 0.65], p=0.47). Strong and statistically significant correlations in movement counts generated from sensors positioned at the elbow were observed between the wired Patriot system and wireless sensors using the activityCounts signal processing package (0.73, 95% CI [0.35, 0.9], p=0.002), with moderate and statistically significant correlations observed when using the MATLAB® signal processing toolbox (PPMCC = 0.67, 95% CI [0.23, 0.88], p=0.0066).

Regards the suturing experiments, strong and statistically significant correlations in movement counts generated from sensors positioned on both hands were observed between the wired Patriot system and the wireless system using the MATLAB® signal processing toolbox (PPMCC = 0.89, 95% CI [0.64, 0.97], p=1.18e-4 for right hand, and 0.86, 95% CI [0.57, 0.96], p=2.99e-4 for left hand). Moderate and statistically significant correlations were observed between the wired Patriot system and the wireless system using activityCounts signal processing (0.67, 95% CI [0.15, 0.9], p=0.018 for right hand, and 0.63, 95% CI [0.09, 0.88], p=0.028 for left hand).

Table 6-5: Summary of relationship and significance between the movement counts generated by the wireless and wired motion analysis systems during simulated complex movement tasks.

Task	Paired sensor position	Software	Signal processing Scripts	Pearson R	95% CI	p value	Mean difference	Lower limit	Upper limit	Critical difference
Hammering	Hand	MatLab	Signal Processing Toolbox	0.59	0.17-0.83	0.009724	-107.44	-245.27	30.38	137.82
Hammering	Elbow	MatLab	Signal Processing Toolbox	0.38	-0.11-0.72	0.12	-133.28	-262.59	-3.96	129.32
Hammering	Hand	Rstudio	activityCounts	0.64	0.25-0.85	3.89E-03	-6111.12	-9276.88	-792.79	4242.04
Hammering	Elbow	Rstudio	activityCounts	0.29	-0.2-0.67	2.37E-01	-1219.17	-2709.11	270.78	1489.94
Screw insertion	Hand	MatLab	Signal Processing Toolbox	0.78	0.46-0.93	0.0005322	-193.27	-314.41	-72.12	121.15
Screw insertion	Elbow	MatLab	Signal Processing Toolbox	0.67	0.23-0.88	0.006546	-232.13	-334.31	-129.96	102.17
Screw insertion	Hand	Rstudio	activityCounts	0.2	-0.35-0.65	0.4696	-4671.73	-7294.84	-2048.62	2623.11
Screw insertion	Elbow	Rstudio	activityCounts	0.73	0.35-0.9	0.002004	-77.67	-242.65	87.31	164.98
Suturing	Right Hand	MatLab	Signal Processing Toolbox	0.89	0.64-0.97	0.0001176	-1727.42	-2285.48	-1169.35	558.06
Suturing	Left Hand	MatLab	Signal Processing Toolbox	0.86	0.57-0.96	0.0002988	-1966.75	-2475.79	-1457.71	509.04
Suturing	Right Hand	Rstudio	activityCounts	0.67	0.15-0.9	0.01813	-2678.17	-4596.49	-759.85	1918.32
Suturing	Left Hand	Rstudio	activityCounts	0.63	0.09-0.88	0.02791	-1850.92	-3372.31	-329.53	1521.39

Figure 6-28: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion analysis systems with MATLAB® Signal Processing for simulated hammering and screw insertion.**

HAMMERING SCREW INSERTION

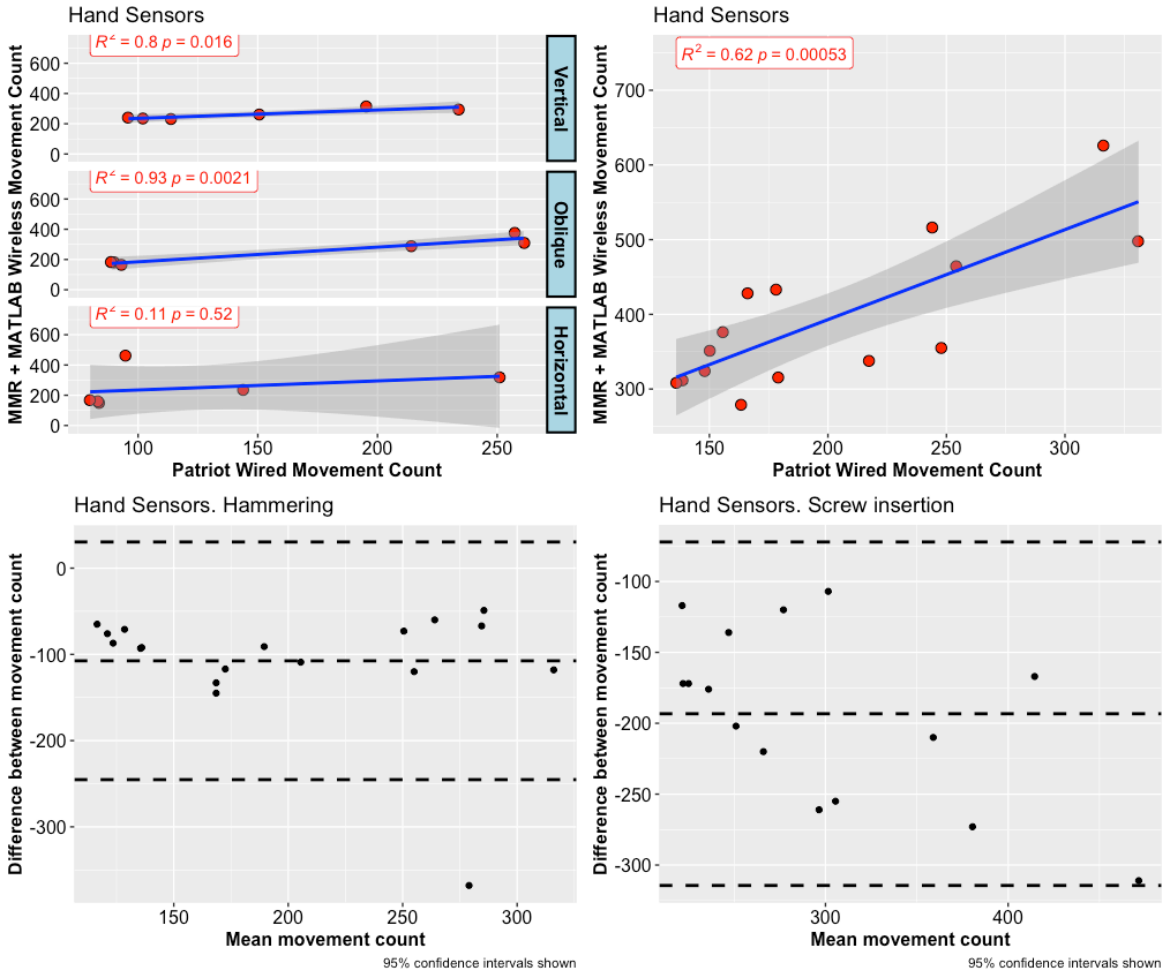


Figure 6-29: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion analysis systems with RStudio activityCounts signal processing for simulated hammering and screw insertion.**

HAMMERING SCREW INSERTION

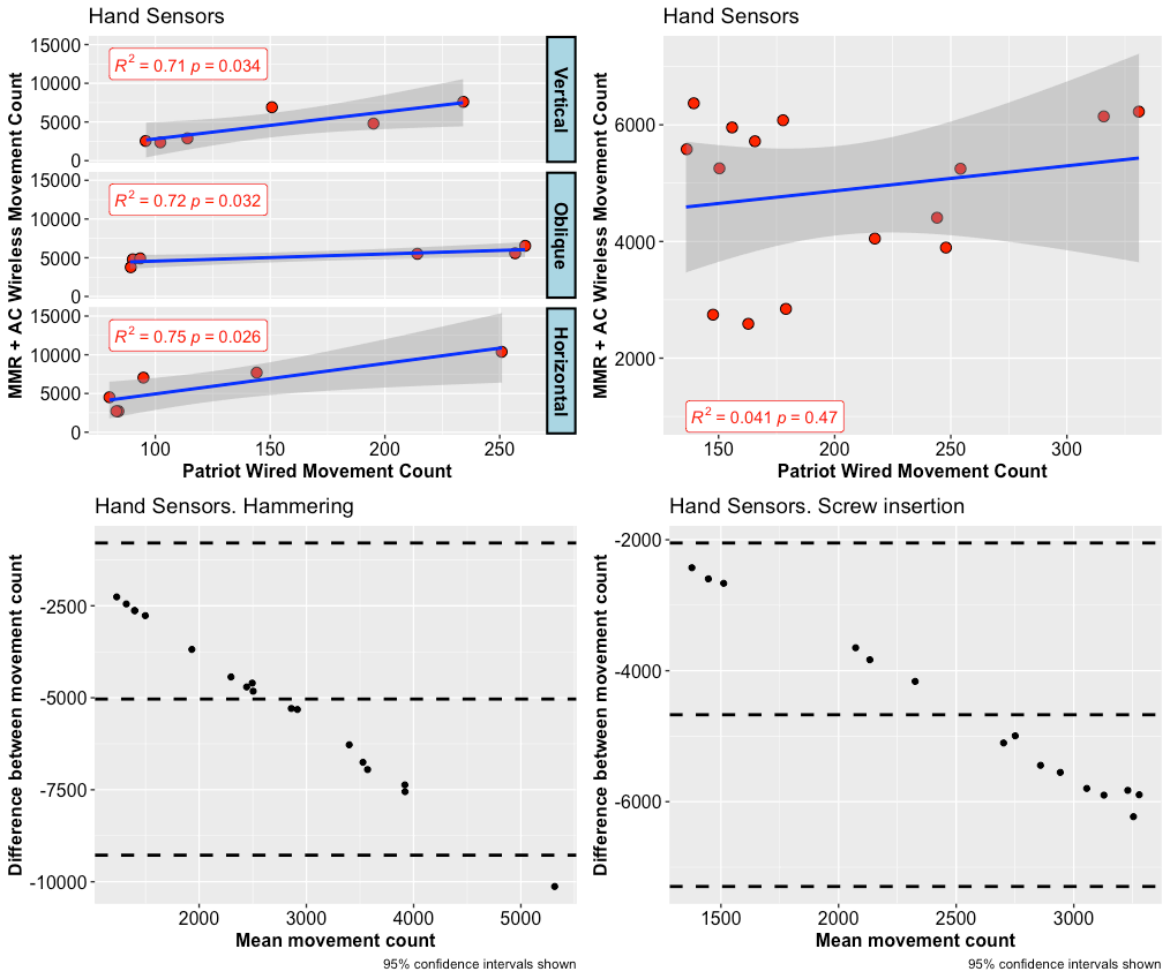


Figure 6-30: **Bland-Altman and scatter plots of movement counts generated by paired elbow sensors from the wired and wireless motion analysis systems with MATLAB® Signal Processing for simulated hammering and screw insertion.**

HAMMERING SCREW INSERTION

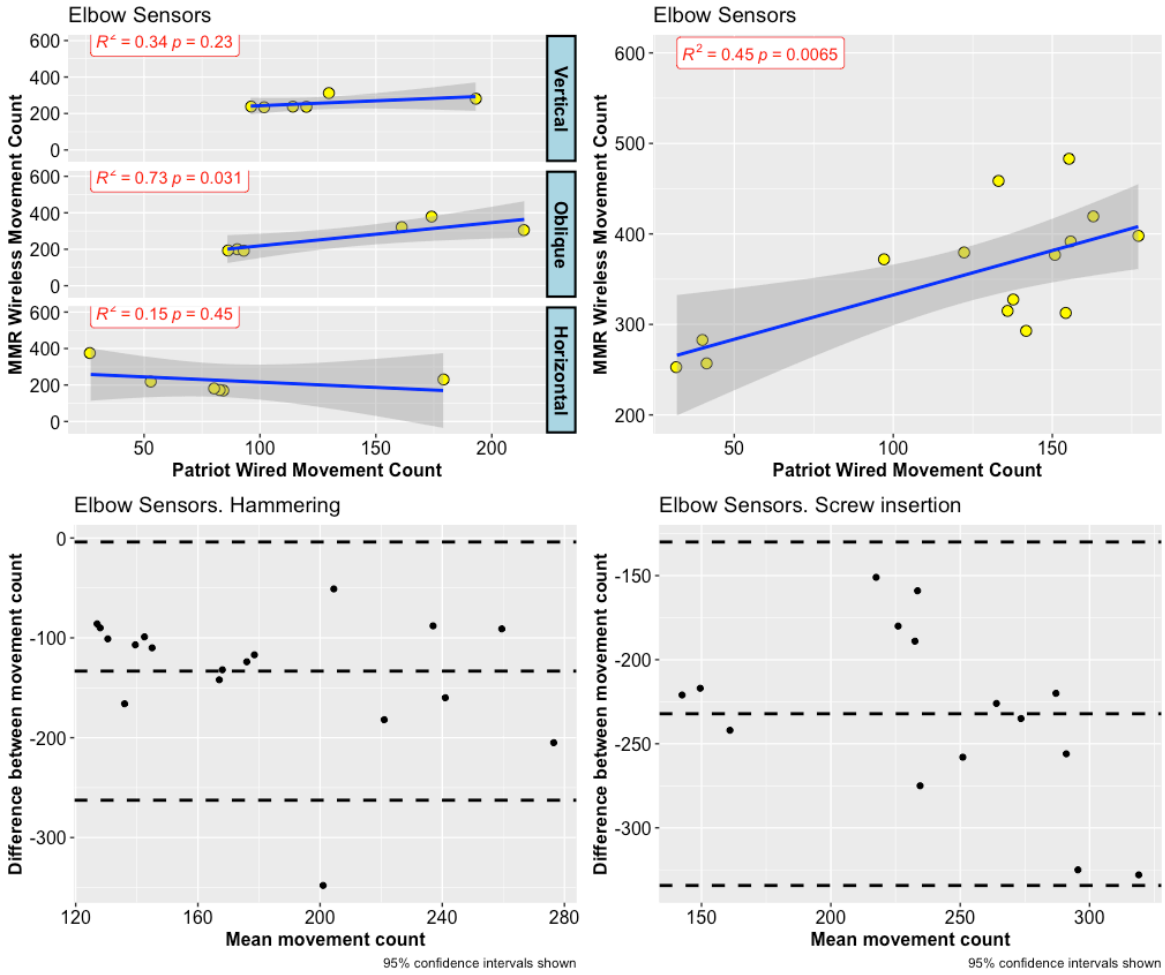


Figure 6-31: **Bland-Altman and scatter plots of movement counts generated by paired elbow sensors from the wired and wireless motion analysis systems with RStudio activityCounts signal processing for simulated hammering and screw insertion.**

HAMMERING SCREW INSERTION

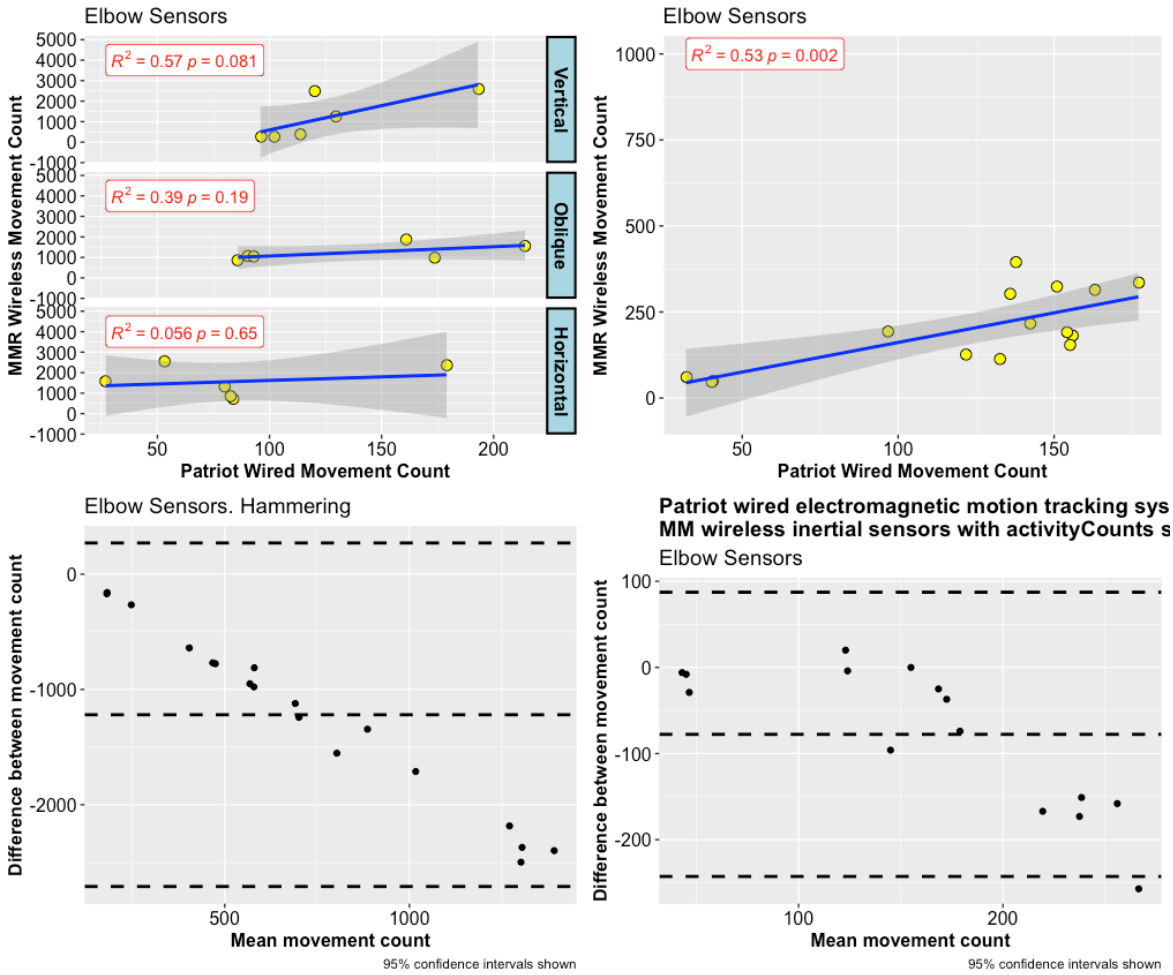


Figure 6-32: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion analysis systems with MATLAB® Signal Processing for simulated suturing.**

RIGHT HAND LEFT HAND

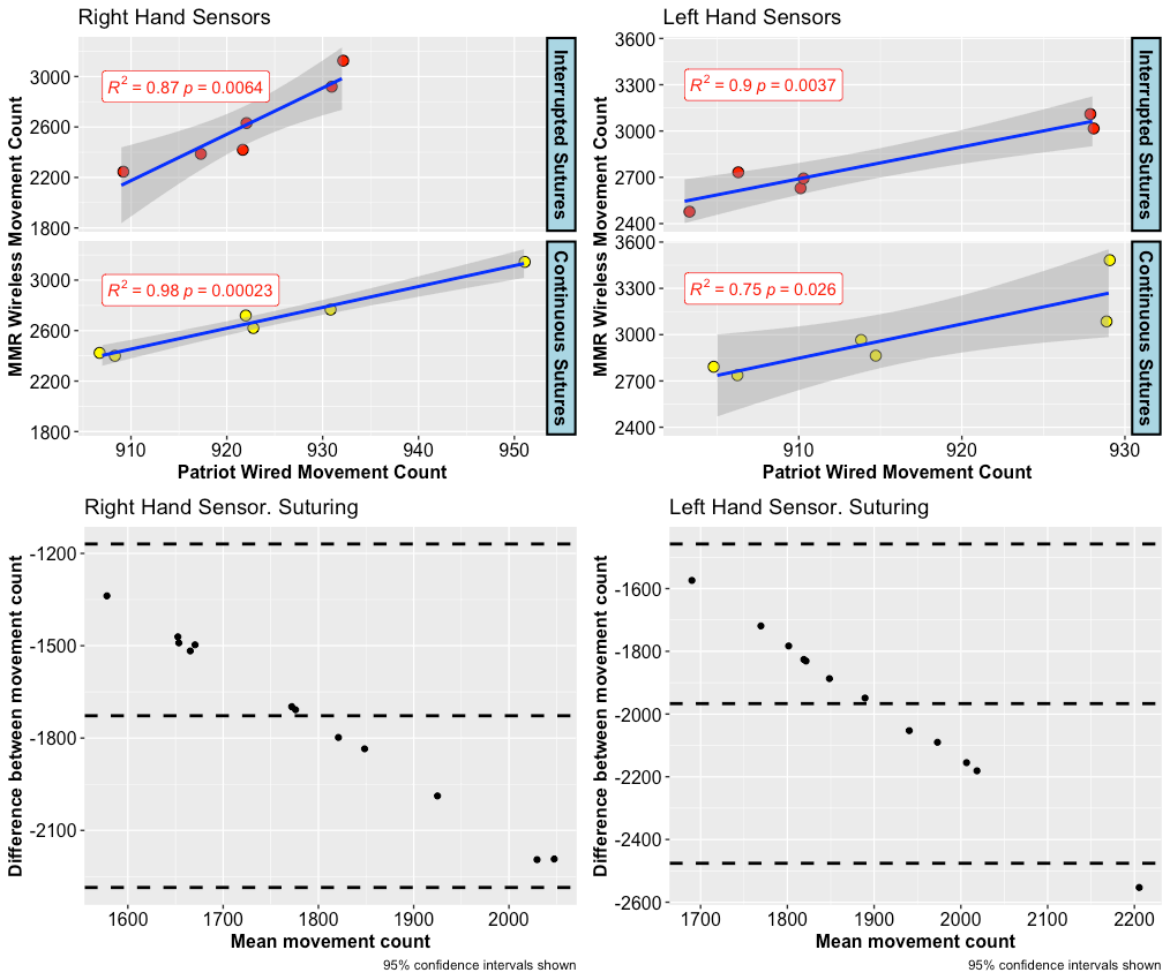
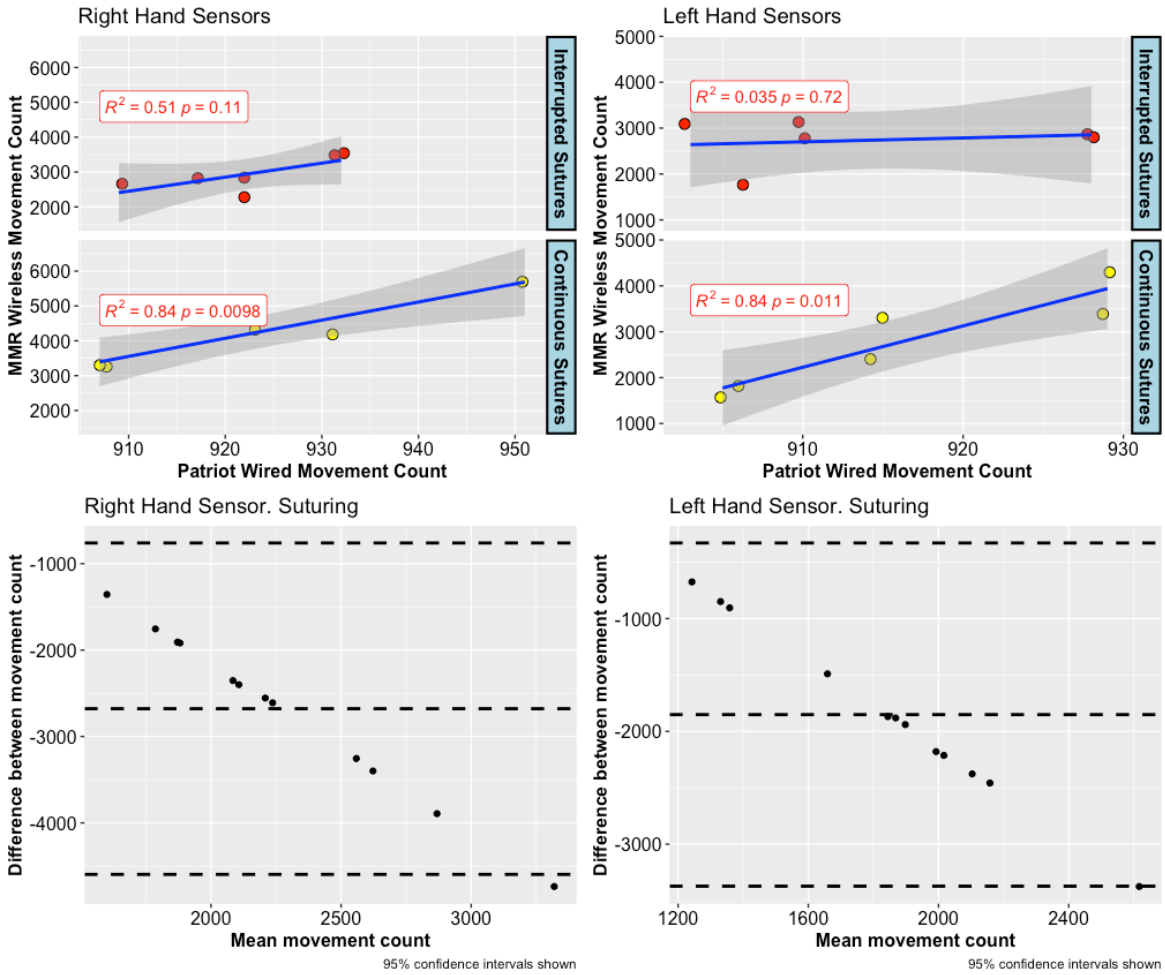


Figure 6-33: **Bland-Altman and scatter plots of movement counts generated by paired hand sensors from the wired and wireless motion analysis systems with RStudio activityCounts signal processing for simulated suturing.**

RIGHT HAND LEFT HAND



6.4.3.3 Scalar magnitude of linear acceleration during complex tasks

The primary aim of this analysis is to determine the MLA peaks generated at the hand and elbow during hammer swings, and to assess any correlation between these readings. This information is used to determine both the range and threshold of MLA values associated with performing this task-specific complex movement. Correlations between the MLA values obtained from sensors at the elbow and hand may also theoretically be used to determine the MLA applied at the hand intra-operatively when data is only obtained from inertial sensors positioned at the elbow. The scalar MLA for the wireless inertial motion data was calculated for all 57 complex movement task experiments using the root mean squared (RMS) technique. Data analysis and visualisation from four individual experiments (J1/K1/L1/P1) with paired wireless MMR inertial sensors at the hand and elbow is presented to highlight the differences in MLA during vertical (J1), horizontal (K1), oblique (L1), and rotational (P1) movements. Paired inertial sensor data at the hand and elbow was not obtained for the suturing experiments as the sensors were positioned over both hands. Discrete peaks in MLA would not be expected in hand motion data whilst suturing as this task requires smoother movements with a low MLA.

Distribution of MLA data

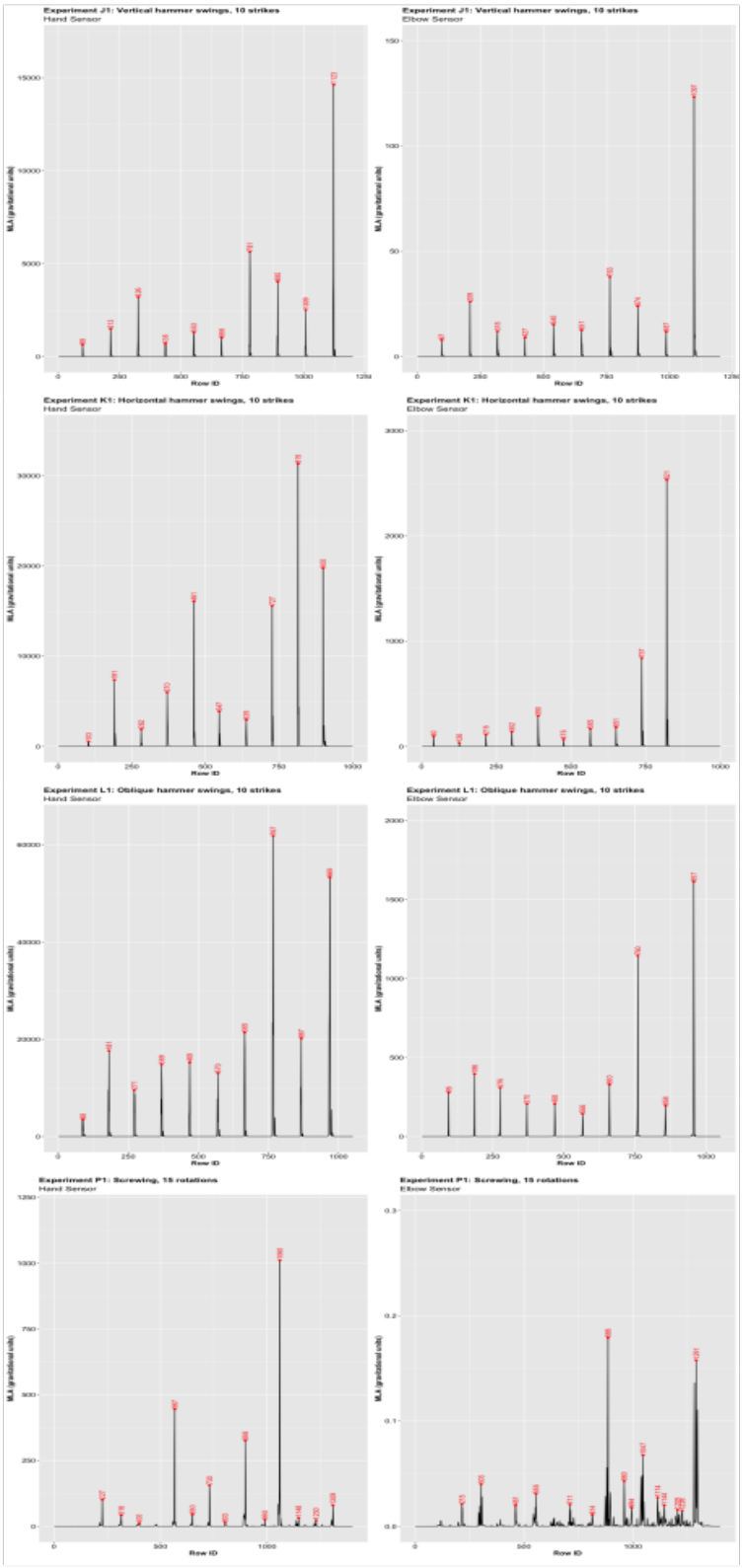
The Shapiro-Wilk test was used to determine the distribution of MLA data for each experiment. The p-value for both sensors (hand and elbow) for experiments J1, K1, L1, and P1 were all < 2.2e-16, indicating that the data were not normally distributed. Density plots indicated a positive skew to the data, with the mean average greater than the median average, and a long upper tail. Non-parametric statistical tests and the use of median and interquartile ranges are therefore justified for reporting descriptive statistics relating to the distribution of MLA data.

MLA data visualisation

The ggpmisc package in RStudio was used to locate and tag peaks in MLA using the pre-defined timespan and amplitude parameters. (304) The MLA for both hand and elbow sensor data has been plotted in line graphs in figure 6-34.

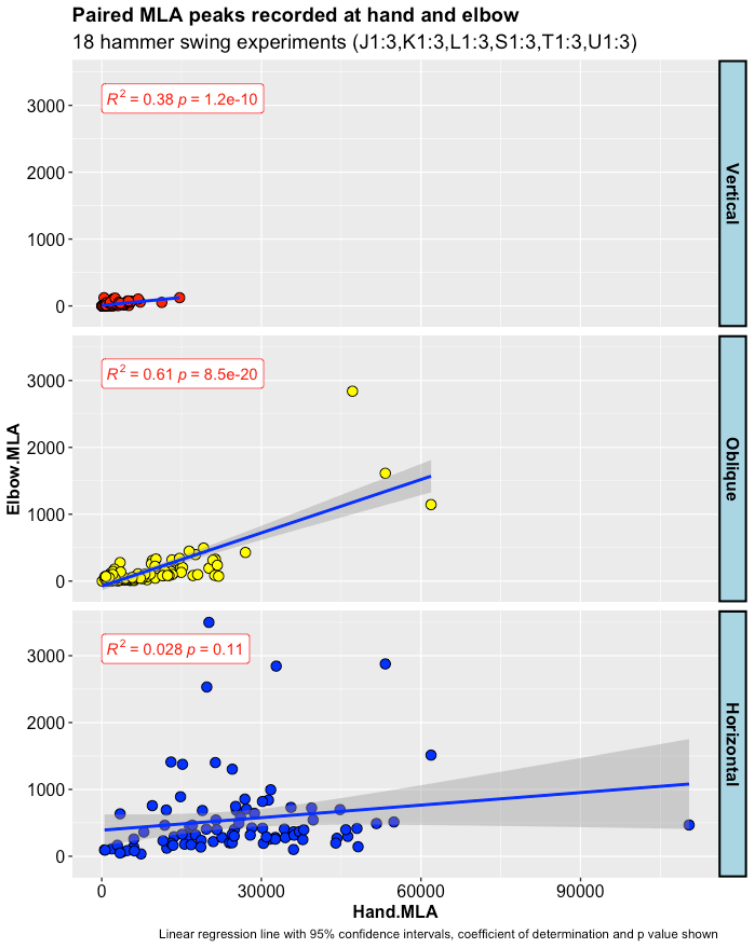
Figure 6-34: **Line graphs of MLA recorded by paired wireless inertial sensors positioned at the hand and elbow during simulated hammer swings.**

Vertical, horizontal, and oblique hammer swings and screw insertion tasks shown.



The peaks in MLA appear to correlate with rapid deceleration during the hammer strikes (experiments J1, K1, L1), and at the end of full supination of the forearm (experiments P1) when an abrupt deceleration occurs. The MLA peaks from both hand and elbow sensors are better defined during the hammer swings than during rotational movements. This allows the paired peaks in MLA during hammer swings to be extracted from the data frame using their tagged row numbers. These paired peaks in MLA may then be visualised in a scatterplot, and both correlations and linear regression analysis performed to determine any relationship. The paired peaks in MLA from inertial sensors positioned at the hand and elbow for 18 hammer swing experiments have been plotted in figure 6-35, with horizontal facets relating to the hammer swing plane of movement.

Figure 6-35: **Scatterplot demonstrating the relationship between peaks in MLA recorded by paired wireless inertial sensors positioned at the hand and elbow during hammer swing experiments.**



The median MLA recorded during the simulated hammer swing experiments was 52455g (514407.8m/s^2) for sensors positioned at the hand (IQR 170909g), and 74.447g (730.07m/s^2) for sensors positioned at the elbow (IQR 2748.48g), respectively. The maximum MLA recorded was 1104023g (1082679m/s^2) for sensors positioned at the hand, and 3498.33g (34306.88m/s^2) for sensors positioned at the elbow.

Table 6-6: **Summary of MLA (gravitational units) data distribution for paired hand and elbow sensors during simulated hammer swings.**

Sensor position	Minimum MLA	Q1 MLA	Median MLA	Q3 MLA	Maximum MLA	IQR
Hand	0	1437	52455	18865	1104023	170909
Elbow	0.005	15.17	74.45	295.43	3498.3	2748.5

Overall, moderate, and statistically significant corelations were observed between the paired hand and elbow peak MLA across these experiments (PPMCC 0.54, 95% CI [0.45 - 0.62], p<0.001). The PPMCC and linear regression relationship was observed to change depending upon the plane of movement of the hammer swing, with strong and modest statistically significant correlations observed during oblique and vertical hammering movements, respectively. Both movements are commonly used by surgeons during THR. Weak and statistically insignificant correlations were observed for horizontal hammering movements, which are rarely used in THR.

Table 6-7: **Summary of relationship and significance between paired hand and elbow MLA during simulated hammer swings.**

Task	Plane of Movement	Sensor Hardware	Connection	Position	Software	Pearson R	95% CI	p value	Linear regression intercept	Linear regression coefficient
Hammering	Vertical	MMR	Wireless	Hand	Rstudio	0.61	0.47-0.73	1.25E-10	725.98	48.42
Hammering	Oblique	MMR	Wireless	Elbow	Rstudio	0.78	0.69-0.85	< 2.2e-16	5327.93	23.03
Hammering	Horizontal	MMR	Wireless	Elbow	Rstudio	0.17	-0.04-0.36	1.13E-01	23013.02	4.529
Hammering	Overall	MMR	Wireless	Elbow	Rstudio	0.54	0.45-0.62	< 2.2e-16	7911.13	17.33

6.5 Study C: Intra-operative feasibility trial of wireless motion analysis system

6.5.1 Aims

The aims of this study are to:

1) Assess the feasibility of using the novel wireless motion analysis system in the clinical environment of an operating room.
2) Assess the content validity of the novel wireless motion analysis system against observed hammer strikes during primary total hip replacement.

6.5.2 Methods

Ethical Approval

This study was conducted under ethical approval from the NHS Research Ethics Committee (REC reference 19/SC/0492, IRAS application 270167), and approval from both the Oxford University Hospitals Joint Research Office and Trust Management, and University of Oxford Clinical Trials and Research Governance (CTRG) (reference: 14471) (Appendix E).

Participants

A total of seven surgeons (Consultants n=4, Specialty Registrars n=3) were recruited to participate in this study. Six participants were right-hand dominant males (Consultants n=4, Specialty Registrars n=2), and a single participant was right-hand dominant female (Specialty Registrar). Intra-operative motion data were collected for a total of ten patients undergoing elective primary THR in the study locations outlined below. All patients provided informed written consent.

Location

This study was conducted on patients undergoing routine elective THR within the operating theatre complexes at the Nuffield Orthopaedic Centre (Oxford University Hospitals NHS Foundation Trust), and Wycombe General Hospital (Buckinghamshire Healthcare NHS Trust).

Motion analysis systems and metrics

The novel wireless motion analysis system based upon MMR® inertial sensors was used in this study. The hardware, software, and data analysis techniques used for this system have been described in section 6.2.2. The MMR® inertial sensors were positioned over the surgeons elbows as described in section 6.3.2.

The primary outcome was the collection of fused linear acceleration data from the MMR® inertial sensors. The transfer and processing of motion data for this system is described in section 6.2. This data was analysed for movement counts and MLA for each step of the procedure. MLA data is then used to determine thresholds for hammer swings in the clinical setting by comparing the number of actual hammer swings observed intra-operatively to those calculated using computer software and custom scripts. The results from studies A and B have demonstrated the distribution of MLA peaks for elbow inertial sensor data when performing simple uniplanar movements and simulated hammer swings (Tables 6-4 and 6-8). The maximum MLA peak recorded during simple movements was 1.06g, and the 25th centile (Q1) for hammer swings was 15.17g. Thresholds of 2g, 5g, 10g, 15g, and 25g were trialled using the intra-operative motion data for femoral broaching and acetabular cup impaction steps. These thresholds should avoid counting any simple movements, and thresholds over 15g should capture ~75% of genuine hammer strikes. Any MLA peaks exceeding these thresholds within a specified data frame (time series of MLA data) is calculated using custom scripts in RStudio. These calculated hammer strike counts is compared to the observed hammer strike counts intra-operatively during uncemented acetabular cup impaction and femoral broaching steps.

Peri-operative set-up and protocol for data collection

After anaesthesia and patient set-up, the supervising surgeon and/or participant scrubbed in the usual manner with the motion sensors in position on the lead surgeon's elbows under their sterile gown (figure 6-36). The procedure was completed as planned whilst motion data was streamed wirelessly using BLE and the MetaBase API as described in section 6.2.2. Manual recordings of the timings of each pre-defined step of the operation. The timings data allows synchronisation of motion data to the participants progression throughout the steps of the operation. Data collection stopped when the dressing has been applied to the surgical wound.

Figure 6-36: **Pre-operative sensor positioning and theatre set-up for motion data collection.**



6.5.3 Results

6.5.3.1 Feasibility of using novel wireless motion analysis system intra-operatively

There were no issues securely attaching the sensors over the surgeon participants elbows using Velcro straps. Connecting and streaming motion data at 100Hz sampling rate using BLE technology was uncomplicated, despite the sensors being positioned underneath the surgeons' sterile gowns at a range of 1-2 metres from the receiving tablet device within the operating theatre. The MMR® inertial sensors were used to collect intra-operative motion data successfully during all ten primary THR cases. Seven of these cases were performed by consultants, and three by specialty registrars. Five cases were right THR, and five were left THR, and all cases used hybrid implant fixation (uncemented acetabular cups and cemented femoral stems). Most patients were female (60%), aged between 61-70 years old (50%), overweight (50%), and ASA 3 or 4 (60%). Summary patient characteristics are contained within table 6-8.

The raw motion data was segmented and analysed using the intra-operative timings data to produce movement counts per step of each operation. The summary figures for movement counts and timings per step for the 10 operations may be visualised in the boxplots in figure 6-37. These boxplots have been grouped according to surgeon grade to highlight any differences between groups for step timings and movement counts.

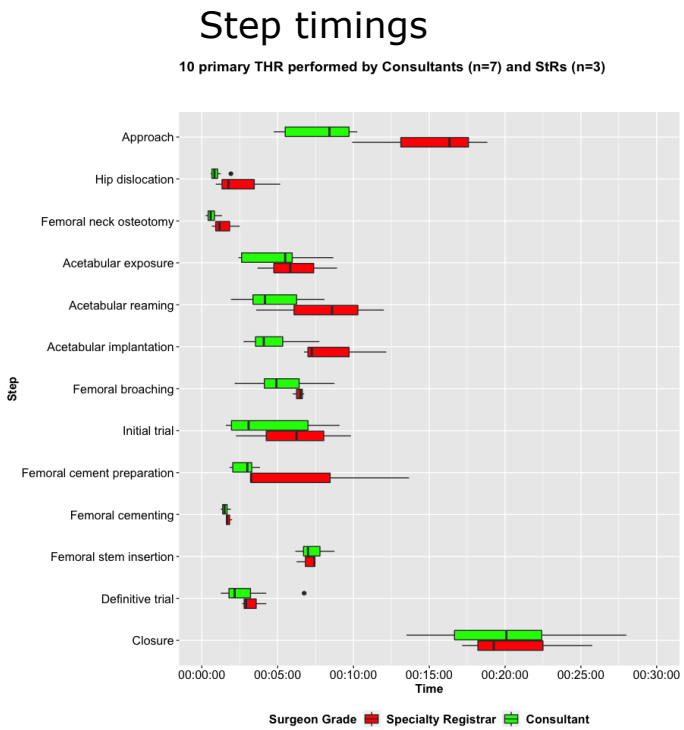
Table 6-8: **Summary of patient characteristics in study C.**

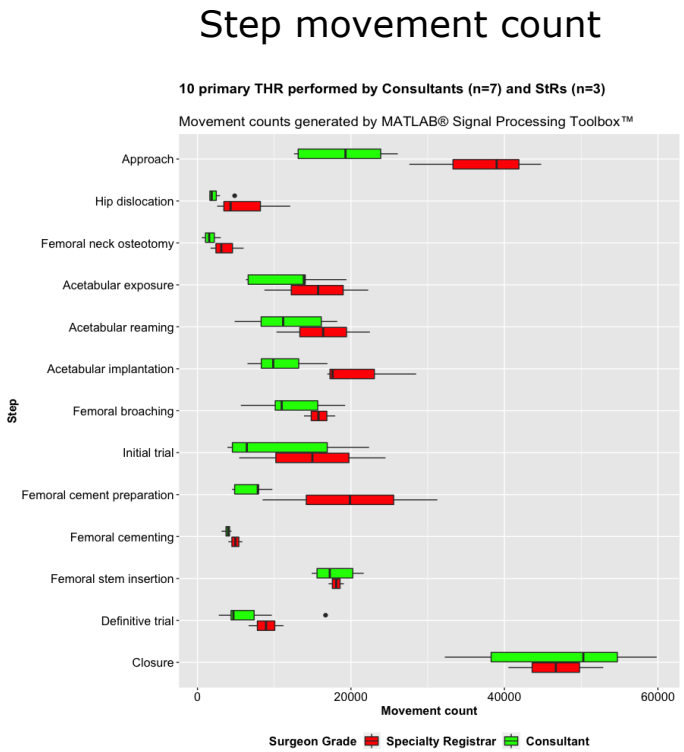
Variable	N = 10[1]
Patient Gender	
Female	6 (60%)
Male	4 (40%)
Patient Age	
51-60	2 (20%)
61-70	5 (50%)
71-80	2 (20%)
81-90	1 (10%)
Patient BMI	
Normal	2 (20%)
Overweight	5 (50%)
Obese	1 (10%)
Morbidly Obese	2 (20%)
Patient ASA	
1/2	4 (40%)
3/4	6 (60%)
THR side	
RIGHT	5 (50%)
LEFT	5 (50%)

[1] n (%)

Figure 6-37: **Step timings and movement counts during primary hybrid THR according to surgeon grade.**

Wireless IMU data analysed using MATLAB® Signal Processing Toolbox™





6.5.3.2 Content validation of hammer strikes during primary total hip replacement

Statistical analysis of the MLA data for the femoral broaching and acetabular cup impaction steps of each of the ten primary THR was performed using the thresholds of 2g, 5g, 10g, 15g, and 25g for counting a hammer strike. The counts generated at each threshold were compared to those observed intra-operatively to determine the optimum threshold for counting hammer strikes using MLA data. The observed and calculated counts are summarised in table 6-9.

Table 6-9: **Summary of observed and calculated hammer strike counts at differing MLA thresholds during cup impaction and femoral broaching steps of a THR.**

Surgeon grade	Acetabular Cup Hammer Strike Count						Femoral Broaching Hammer Strike Count					
	Observed	25g	15g	10g	5g	2g	Observed	25g	15g	10g	5g	2g
Specialty Registrar	95	95	95	96	97	100	142	61	80	95	121	150
Consultant	123	82	87	89	101	128	130	73	87	102	120	147
Consultant	45	43	45	48	59	78	68	16	27	40	39	52
Consultant	13	15	17	17	23	39	67	49	56	60	71	95
Specialty Registrar	53	26	28	29	39	54	46	56	69	72	84	110
Consultant	28	15	17	21	36	66	200	130	149	162	188	237
Consultant	27	28	28	28	28	29	152	52	58	61	68	84
Consultant	44	23	26	28	33	37	121	38	45	50	57	64
Consultant	31	27	28	28	32	35	230	99	126	140	176	219
Specialty Registrar	32	4	9	14	22	44	237	193	210	229	247	278

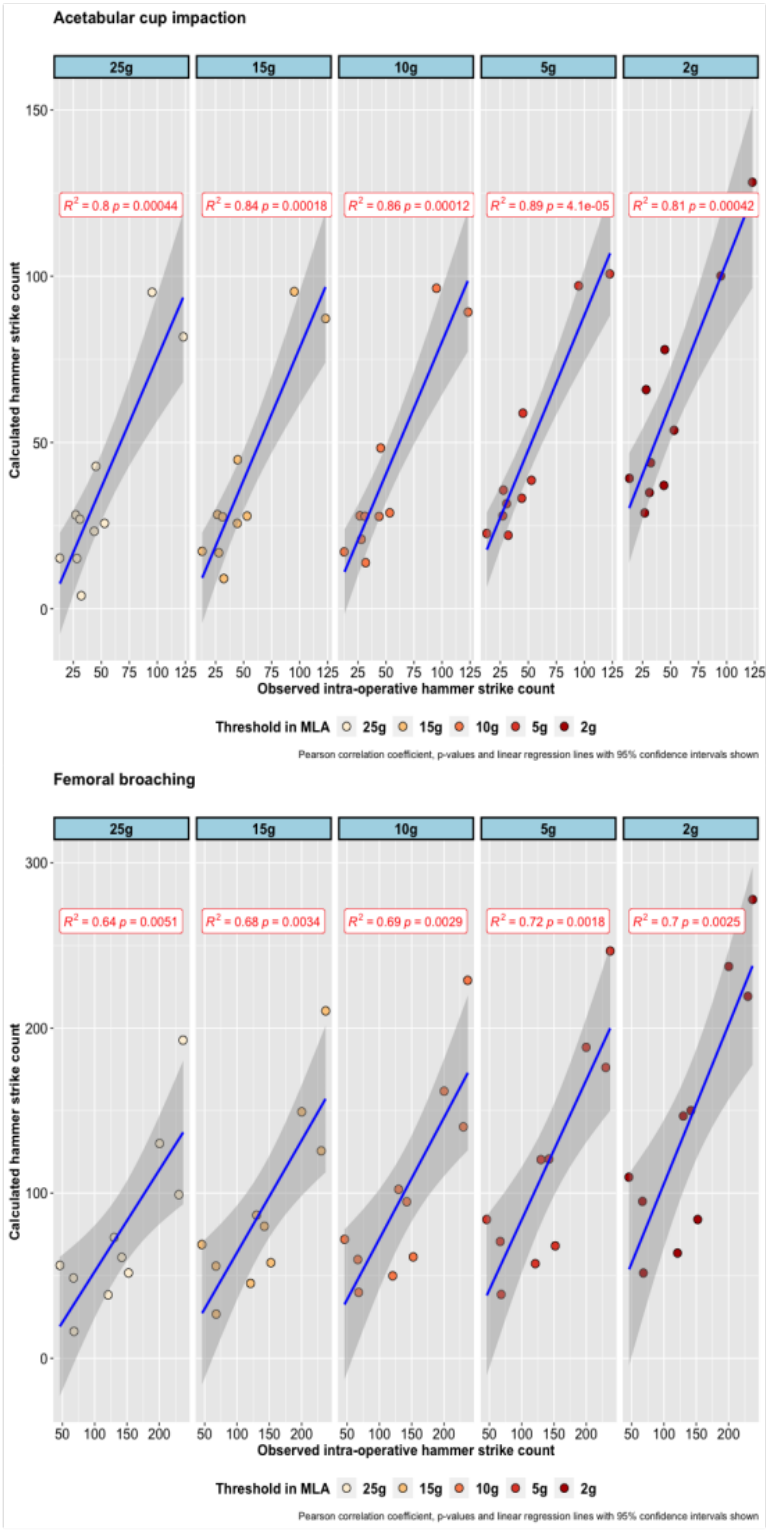
Scatterplots in figure 6-38 represent the relationship between the calculated hammer strike counts generated using the MLA data (y axis) against the observed intra-operative hammer strike counts for the femoral broaching and acetabular cup impaction steps of the operation (x axis). The scatterplots for each step are faceted according to the MLA thresholds used to calculate the hammer strike count (vertical facets). Linear regression (R^2) and significance (p-values) are printed in red within the faceted scatterplots. Summarised PPMCC, significance (p-values), and linear regression modelling outputs for each step and MLA threshold are summarised in table 6-10.

Table 6-10: **Summary of relationship and significance between observed and calculated hammer strike counts at differing MLA thresholds during cup impaction and femoral broaching steps of a THR.**

Step	MLA Threshold (g)	Pearson R	95% CI	p value	Linear regression intercept	Linear regression coefficient
Cup impaction	25	0.9	0.61-0.98	0.000439	-2.58	0.78
Cup impaction	15	0.92	0.68-0.98	0.000185	-1.02	0.79
Cup impaction	10	0.93	0.71-0.98	0.000116	0.76	0.8
Cup impaction	5	0.94	0.77-0.99	4.10E-05	7.22	0.81
Cup impaction	2	0.9	0.62-0.98	4.19E-04	19.2	0.85
Femoral broaching	25	0.8	0.35-0.95	5.15E-03	-9.02	0.6154
Femoral broaching	15	0.82	0.4-0.96	0.003354	-3.94	0.68
Femoral broaching	10	0.83	0.42-0.96	0.00291	-1.23	0.73
Femoral broaching	5	0.85	0.48-0.96	0.001815	-0.9	0.85
Femoral broaching	2	0.83	0.44-0.96	0.002545	9.6	0.96

These results demonstrate that an MLA threshold of 5g produced the strongest correlations between observed and calculated hammer strike counts during both acetabular cup impaction (PPMCC 0.94, 95% CI [0.77 - 0.99], p=4.1e-05) and femoral broaching (0.85, 95% CI [0.48 - 0.96], p=0.0018). This threshold and methodology is used to determine the number of hammer strikes performed by each surgeon during acetabular cup impaction and femoral broaching for each THR performed in the clinical studies in chapter 8.

Figure 6-38: **Scatterplots of hammer strike counts generated using MLA data from wireless inertial sensors against observed intra-operative hammer strike counts during acetabular cup impaction and femoral broaching steps of a primary THR.**



6.6Discussion

6.6.1 Summary of findings

The bespoke rigs developed to simulate both simple planar movements (study A) and complex movements (study B) were effective and provided a robust laboratory environment to investigate the content and concurrent validity of the novel wireless motion analysis system against a validated wired electromagnetic system. The movements required to perform these diverse range of tasks reflect the scale and complexity of upper limb movements which are likely to be encountered by surgeons in the clinical environment of an operating theatre.

The results from study A demonstrate that movement counts generated by both wired and wireless motion analysis systems are significantly and highly correlated with actual movement counts observed during simple tasks performed on the custom triplanar simulation rig. The positioning of sensors either on the hand or elbow clearly affects the motion data recorded and subsequent movement count generated by both systems. Higher correlations were noted between the calculated and observed movement counts for both methods of signal processing (MATLAB® and RStudio) for the wireless inertial sensors positioned on the hand in comparison to the elbow. However, movement counts generated from inertial sensors at the hand and elbow were more highly correlated to actual movement counts when using the MATLAB® signal processing toolbox in comparison to the activityCounts package in RStudio. Furthermore, marginally higher correlations were noted between the calculated and observed movement counts for wired electromagnetic sensors positioned on the elbow in comparison to the hand. During simple tasks, the movement counts generated specifically from elbow sensors were most highly correlated with actual movement counts using the wired electromagnetic system, followed closely by the wireless sensors with MATLAB® signal processing toolbox, and finally the wireless sensors with RStudio activityCounts signal processing. These findings validate the use of metrics obtained from wireless inertial sensors positioned at the elbows and analysed using the MATLAB® signal processing toolbox technique for determining movement counts during simple triplanar tasks. The linear regression coefficient of determination of

actual compared with measured movement counts using the wireless inertial sensors positioned at the elbows was 12.58, indicating that measurements obtained using this system represent approximately 12.58 times the actual movement count performed during these tasks.

The concurrent validation analysis performed in study A demonstrated stronger correlations in movement counts between the validated wired system and the inertial sensor data processed using MATLAB® in comparison to RStudio. The correlations were again stronger for the movement counts generated from paired hand sensors from both wired and wireless systems in comparison to sensors positioned at the elbows. However, for the inertial sensors positioned at the elbow, movement counts generated using the MATLAB® signal processing toolbox were more highly correlated with the wired electromagnetic system in comparison to those generated using the RStudio activityCounts package. Correlation coefficients, including PPMCC, describe the linear relationship between two sets of data, but not the level of agreement between them. BA plots and statistics are recognised methods to assess the level of agreement between two quantitative measurement tools. (307, 308) BA analysis demonstrated lower mean and critical differences in movement counts from elbow inertial sensor data processed using MATLAB® (-795.78 and 1075.09 respectively) in comparison to RStudio (-1613.6 and 5947.94 respectively). Linear regression analysis was not necessary for any of the concurrent validation studies between the wired and wireless systems because the wired system is not used for any intra-operative motion tracking. Therefore, the relationship and coefficient of determination (R^2) between the movement counts generated by these two systems is irrelevant for the clinical application of the wireless motion analysis system alone. The positive skew observed in the distribution of MLA data in studies A and B justifies the use of median and IQR for reporting descriptive statistics of this data. The paired peaks in MLA data observed from both hand and elbow inertial sensors during simple uniplanar movements allows thresholds characteristic of these movements to be established. The results suggest a maximum MLA of 3.55g (34.8m/s2) for sensors positioned at the hand, and 1.06g (10.4m/s2) for sensors positioned at the elbow during such movements. Furthermore, a positive and highly significant correlation was observed between the MLA measured at the hand and elbow (PPMCC = 0.84, 95% CI [0.79, 0.87],

p <0.001). The linear regression coefficient of determination of this relationship was 3.3, indicating that on average hand MLA is over three times higher than that measured at the elbow during simple uniplanar movement tasks.

The results from study B demonstrate that movement counts generated by the wired and wireless motion analysis systems are significantly and highly correlated with actual movement counts observed during complex multiplanar tasks. These tasks were designed specifically to simulate tasks commonly undertaken during THR operations. However, content validation analysis could only be performed for the tasks involving a known number of actual movements (hammer swing and screw insertion). The results of both the simulated hammer swinging, and screw insertion experiments demonstrate higher correlations between the calculated and observed movement counts for the wired and both methods of wireless signal processing for sensors positioned on the hand in comparison to the elbow. Movement counts generated from inertial sensors at the hand and elbow during hammer swinging were marginally better correlated to actual movement counts when processed using the activityCounts package in comparison to the MATLAB® signal processing toolbox. However, the opposite was true during screw insertion experiments, when both hand and elbow inertial sensor data processed by MATLAB® were more significantly correlated with actual movement counts, and not correlated at all when processed using the activityCounts package. In fact, the movement counts generated from wireless data processed with the activityCounts package demonstrated negative associations with actual movement counts during some simulated screw insertion experiments. Movement counts generated by the elbow inertial sensor data and processed by MATLAB® were the most significantly correlated with actual movement counts from all the wireless motion data at the elbow across all the screw insertion experiments. When using the wired electromagnetic system, significant correlations were noted between the calculated and observed movement counts for the hand, but not elbow sensors during simulated screw insertion. This suggests poor sensitivity of the electromagnetic motion tracking system in detecting rotational forearm movements using sensors positioned at the elbow. During simulated hammering experiments, the movement counts generated specifically from elbow sensors were most highly correlated with actual movement counts using the

wireless sensors with RStudio activityCounts signal, followed closely by the wireless sensors with MATLAB® signal processing toolbox, and finally the wired electromagnetic system. During simulated screw insertion experiments, the movement counts generated specifically from elbow sensors were only significantly correlated with actual movement counts using the wireless sensors with MATLAB® signal processing toolbox. Movement counts generated by wireless sensors with RStudio activityCounts signal processing and the wired electromagnetic system were both not significantly correlated with actual movement counts. The poor performance of the elbow sensors from the wired electromagnetic system in accurately estimating movement counts during simulated hammer swings and screw insertion precludes any inferences being made regarding their correlation with the movement counts generated by the wireless system in the concurrent validation analysis performed in study B. However, movement counts generated by hand sensors on the wired electromagnetic system for simulated hammer swings were significantly correlated to both methods of signal processing in the inertial sensor data. Conversely, across the simulated screw insertion experiments only movement counts generated from inertial hand sensors using the MATLAB® signal processing toolbox were found to significantly correlate with the hand sensors on the wired electromagnetic system. The simulated suturing experiment results demonstrate superior and significant correlations in movement counts for both hands between the wired electromagnetic system and those generated using the MATLAB® signal processing toolbox for inertial sensor data. These findings again validate the use of metrics obtained from wireless inertial sensors positioned at the elbows and analysed using the MATLAB® signal processing toolbox technique for determining movement counts during complex tasks, such as hammering, screw insertion and suturing. Strong and statistically significant correlations between actual and measured movements were observed using this method for both screw insertion and hammering.

The paired peaks in MLA data observed from both hand and elbow inertial sensors during simulated hammer swings allowed thresholds characteristic of these movements to be established. The results suggest a maximum MLA of 52455g (514407m/s2) for sensors positioned at the hand, and 74.45g (730m/s2) for sensors positioned at the elbow during such movements. Interestingly, a positive and highly significant correlation was observed between the MLA measured at the hand and elbow for vertical and oblique, but not horizontal hammer swings. The linear regression coefficient of determination was also observed to vary significantly depending upon the plane of hammer swing. The variation in biomechanics used during these different hammer swing techniques obviously affects the MLA generated at both the hand and elbow. However, as mentioned previously, most surgeons observed over the course of this research prefer using either a vertical or oblique plane of hammer swing in a clinical setting when performing THR. The 25th centile (Q1) value for elbow sensor MLA (15.17g) observed during simulated hammer swings in study B served as a guide to set thresholds for calculating the number of hammer swings intra-operatively in study C. Assessing the feasibility of using the novel wireless motion analysis system in a clinical setting also provided the opportunity to test these thresholds for analysing intra-operative motion data. The results from study C have demonstrated that using a threshold of 5g MLA when calculating hammer strikes using elbow inertial sensor data is the most highly correlated with the number observed intra-operatively during both femoral broaching and acetabular cup impaction steps of a primary hybrid THR. This method of determining the number of hammer strikes is clearly more accurate than using the MATLAB® signal processing toolbox as used in studies A and B.

6.6.2 Limitations of study

Further experiments using the same simulation rigs in studies A and B with higher movement repetitions would theoretically increase the reliability of results generated. The observed tendency for greater discrepancy in higher movement counts between the wired and wireless systems in the concurrent validation studies A and B suggests that increased time and movements are associated with a reduced agreement between these systems, and further experiments to investigate this phenomenon would be useful. Within study C, the intra-operative MLA data was analysed using only five thresholds. Trialling more thresholds may increase the correlation achieved between the observed and calculated hammer strikes using the intra-operative MLA data from inertial sensors. However, because the correlations were already observed to be either strong (femoral broaching) or very strong (acetabular cup impaction), further analysis within this research was deemed unnecessary. The raw tri-axial linear acceleration and calculated MLA data used in this study are quoted in gravitational (g) units, as this is the primary output unit used in the MMR® inertial sensors. However, g units may be easily converted into the widely accepted international system of units (SI) derived unit for acceleration of meters/second^2 (m/s^2) by multiplication by a factor of 9.80665.

6.7 Conclusions

The practical use of motion sensors in the sterile clinical environment of an operating theatre relies upon their positioning at the elbow, and away from the hand. Therefore, motion analysis metrics generated by inertial sensors positioned at the elbow were therefore of primary interest in this research. The results of studies A and B in this chapter have demonstrated that fused linear acceleration inertial sensor data analysed using the MATLAB® signal processing toolbox methodology has enhanced content and concurrent validity and reliability in comparison to using the RStudio activityCounts package. Very strong and strong statistically significant correlations between actual and measured movements were observed using this method for simple triplanar movements, screw insertion, and hammering, respectively. The linear regression coefficients of determination of actual compared with measured movement counts using this method were 7.9 for screw insertion,

9.33 for hammering, and 12.58 for simple triplanar movements. These findings indicate that measurements obtained using this wireless motion analysis system represent between 7.9 and 12.58 times the actual number of observed movement counts performed during these tasks. Furthermore, the results suggest a maximum MLA of 3.55g (34.8m/s2) for sensors positioned at the hand, and 1.06g (10.4m/s2) for sensors positioned at the elbow during simple movements. The experiments conducted in study C used inertial sensors to successfully collect intra-operative surgeon motion data within the clinical setting of an operating theatre. Importantly, the use of these sensors intra-operatively was well tolerated by surgeons, did not interfere with their movement during the operation or any electronic equipment, and data acquisition was seamless. This feasibility study provides preliminary evidence that inertial sensor hardware used in the novel wireless motion system is both safe and viable for use in this setting. Furthermore, the bespoke scripts used for analysing elbow MLA data has allowed a threshold of 5g to be set which reliably identifies the number of intra-operative hammer strikes either when impacting an acetabular cup or broaching a femur. In conclusion, the collective results from the three linked studies in this chapter have demonstrated the validity and feasibility in using this novel, low-cost wireless motion analysis system to determine movement counts during simple and complex tasks in both a simulated laboratory and clinical environment. These findings support the use of this system and interpretation of the objective metrics generated within the subsequent clinical studies in chapter 8 of this research.

7 Performance assessment in simulated primary total hip replacement

7.1 Introduction

These linked studies aim to determine the cognitive and technical skills performance of consultant orthopaedic surgeons, senior arthroplasty fellows, orthopaedic specialty registrars, and medical students during simulated components of a total hip replacement. The purpose of Study A is to determine if technical skills tasks or cognitive assessments in specific aspects of total hip replacement can differentiate participants on their level of surgical experience (construct validation). Study B assesses if any significant change in performance metrics is seen following a focused simulation-based module within a subset of the specialty registrar participants.

7.2 Study A: Construct validation study of performance metrics in simulated primary total hip replacement.

7.2.1 Aims

The primary aim of this study is to determine if significant differences exist between participants of varying levels of surgical experience in their cognitive or technical skills performance in simulated aspects of total hip replacement.

7.2.2 Methods

Study design

This is a prospective observational study.

Ethical Approval

This study was conducted under ethical approval from the Medical Sciences Interdivisional Research Ethics Committee of the University of Oxford Central University Research Ethics Committee (CUREC) (MS-IDREC-R57808/RE001; Appendix D.1).

Participants

Consultant orthopaedic surgeons (consultants), senior orthopaedic arthroplasty fellows (fellows), orthopaedic specialty trainees (StRs), and medical students were invited to participate in this study.

The inclusion criteria were:

- The participant is willing and able to give informed written consent for participation in the study.
- Healthy adults aged 18 years or above.

- Participants include those who are: employed as a consultant orthopaedic surgeon or senior arthroplasty fellow within the Oxford University Teaching Hospitals NHS trust; enrolled as an orthopaedic specialty trainee within the Health Education Thames Valley postgraduate medical deanery; or a clinical medical student at the University of Oxford.

The exclusion criteria were:

- Participant is unwilling, or unable to provide written informed consent.

A rolling recruitment strategy was used for all participants except for the StRs, who were recruited in three separate rounds (outlined in study B, section 7.3). All participants were given a study information sheet prior to providing written informed consent (Appendix D.2).

Location

This Oxford Orthopaedic Simulation and Education Centre (OOSEC), University of Oxford at the Nuffield Orthopaedic Centre.

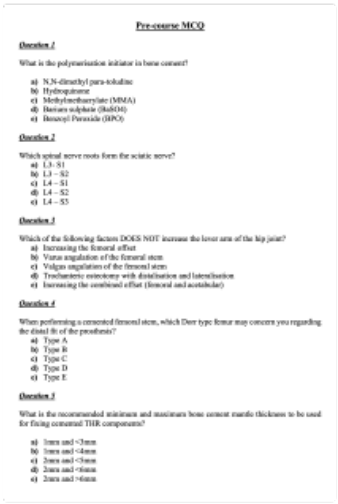
Protocol for task performance assessments

All participants were given written and verbal instructions of the study protocol for task performance assessment prior to data collection. The tasks developed for use in this chapter have been validated in chapter 5. Participants were individually asked to perform up to four tasks, with the order of task performance remaining uniform. The tasks included a 20-question multiple-choice questionnaire (MCQ); component templating exercise; skin marking exercise; and component orientation assessment. Participants were given 30 minutes to complete both the pre-course MCQ (Appendix B.2) and component templating exercise. For the skin marking exercise, participants were asked to sequentially draw their planned skin incisions for both posterior and direct lateral (Hardinge/trans-gluteal) surgical approaches over a simulated model of a left hip. The component orientation task was undertaken using simulated models of the femur and pelvis. The manual method was used to assess component orientation in both models. The femur assessment was performed first, followed

by the pelvis. Using the femur model (figure 7.2), participants were instructed to insert a size 1 collarless polished tapered stem (Taperfit™, Corin Group Ltd., The Corinium Centre, Cirencester, UK) as straight as possible in the coronal plane with 15° anteversion into a simulated cement mantle within a prepared synthetic adult male femur set up in a position to simulate a posterior surgical approach (Sawbones®, Pacific Research Laboratories, Sawbones Europe AB, Limhamn, Sweden). A total of eight separate acetabular cup orientation readings were performed for each participant using two pelvis models (figure 7-2). The first model was a synthetic left adult hemi-pelvis, and the second model used the same synthetic hemi-pelvis surrounded by simulated soft tissues (Sawbones®, Pacific Research Laboratories, Sawbones Europe AB, Limhamn, Sweden). The purpose of using two separate models and eight separate acetabular cup orientation readings was to test the participants ability to achieve a specified cup orientation under increasingly challenging simulated scenarios. Participants were instructed to insert a 56mm uncemented acetabular cup (Trinity™, Corin Group Ltd., The Corinium Centre, Cirencester, UK) in 40° operative inclination (OI) and 20° operative anteversion (OA) for every acetabular cup orientation reading. Participants were firstly instructed to insert the acetabular cup without using the mechanical alignment guide (MAG) and with the model positioned parallel to the floor. Following this, the MAG was used to aid participants orientate cup placement again with the model positioned parallel to the floor. (236, 309) Following this a 6° cranio-caudal downwards tilt was added to the pelvis model to simulate on-table pelvic adduction. (201, 238, 310) Using this set-up two further readings were then taken without, then with the MAG. The same series of readings were then performed in the same order using the pelvis model with simulated soft tissues, which was prepared to simulate a posterior surgical approach to the hip joint. (236)

Figure 7-1: MCQ, component templating, and skin marking exercises.

1. Multiple Choice Questionnaire



Pre-course MCQ

Question 1

What is the polymerisation initiator in bone cement?

a) N,N-dimethyl para-toluidine
b) Hydroquinone
c) Methylmethacrylate (MMA)
d) Barium sulphate (BaSO4)
e) Benzoyl Peroxide (BPO)

Question 2

Which spinal nerve roots form the sciatic nerve?

a) L3–S1
b) L3 – S2
c) L4 – S1
d) L4 – S2
e) L4 – S3

Question 3

Which of the following factors DOES NOT increase the lever arm of the hip joint?

a) Increasing the femoral offset
b) Varus angulation of the femoral stem
c) Valgus angulation of the femoral stem
d) Trochanteric osteotomy with distalisation and lateralisation
e) Increasing the combined offset (femoral and acetabular)

Question 4

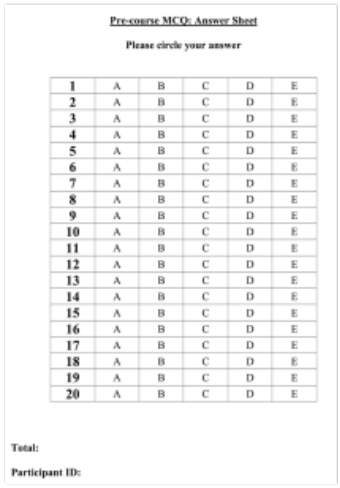
When performing a cemented femoral stem, which Dorr type femur may concern you regarding the distal fit of the prosthesis?

a) Type A
b) Type B
c) Type C
d) Type D
e) Type E

Question 5

What is the recommended minimum and maximum bone cement mantle thickness to be used for fixing cemented THR components?

a) 1mm and <2mm
b) 1mm and <4mm
c) 2mm and <3mm
d) 2mm and <4mm
e) 2mm and >4mm



Pre-course MCQ: Answer Sheet

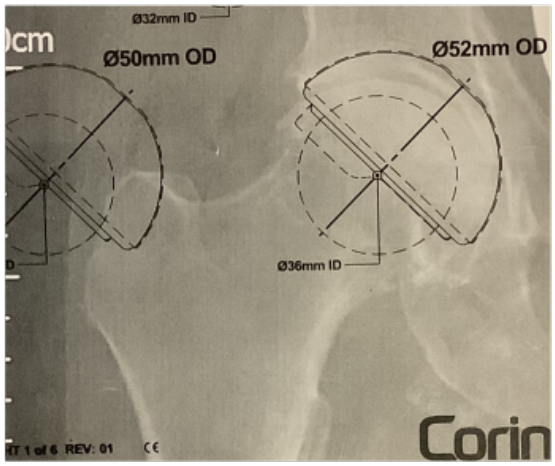
Please circle your answer

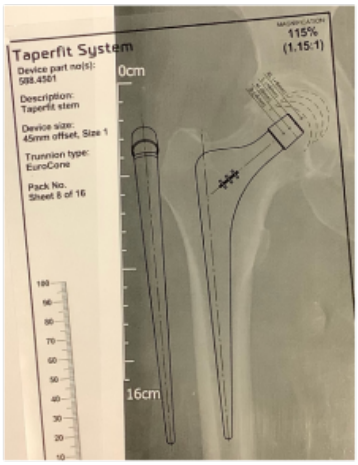
1	A	B	C	D	E
2	A	B	C	D	E
3	A	B	C	D	E
4	A	B	C	D	E
5	A	B	C	D	E
6	A	B	C	D	E
7	A	B	C	D	E
8	A	B	C	D	E
9	A	B	C	D	E
10	A	B	C	D	E
11	A	B	C	D	E
12	A	B	C	D	E
13	A	B	C	D	E
14	A	B	C	D	E
15	A	B	C	D	E
16	A	B	C	D	E
17	A	B	C	D	E
18	A	B	C	D	E
19	A	B	C	D	E
20	A	B	C	D	E

Total:

Participant ID:

2. Component Templating Exercise





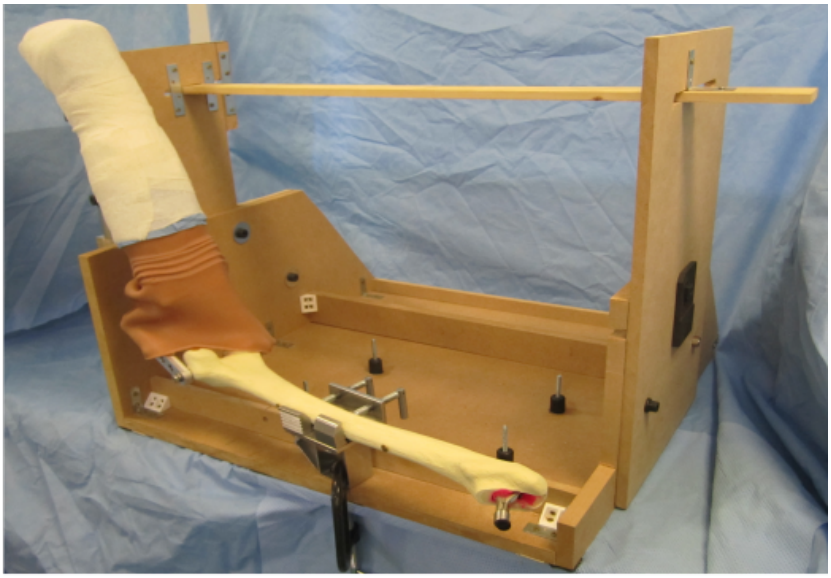


3. Skin Marking Exercise

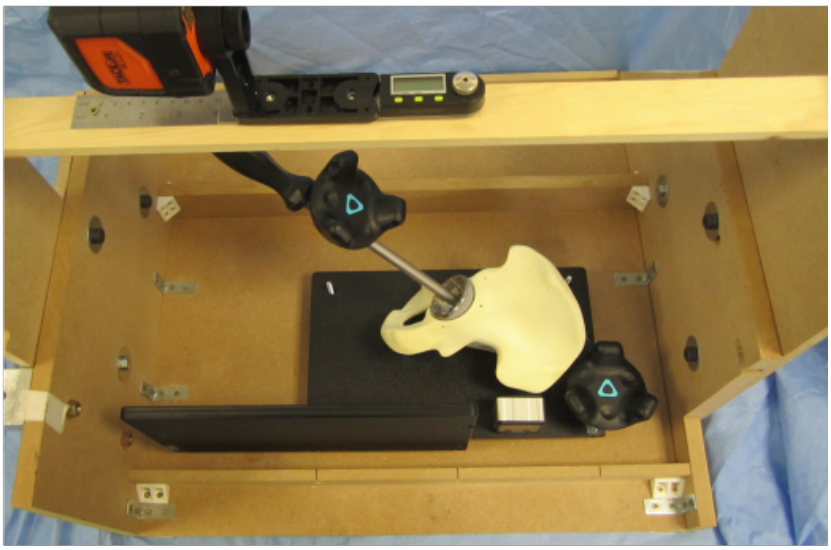


Figure 7-2: Pictures of the models used for the component orientation tasks.

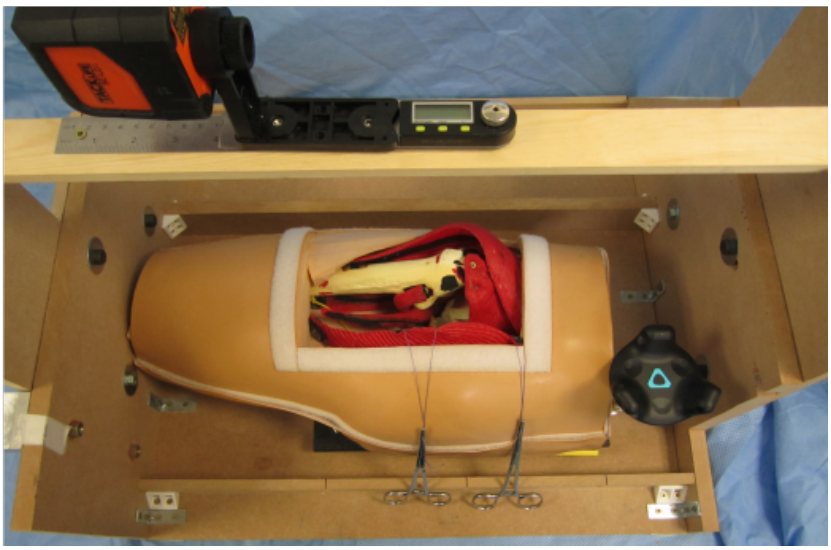
4 A. Femur model



4 B. Hemipelvis model



4 C. Hemipelvis with simulated soft tissue model



The arthroplasty fellows and StRs performed all four tasks. The consultants did not undertake the multiple-choice questionnaire (MCQ) because they were responsible for standard setting. The medical students were not asked to undertake the MCQ, templating or skin marking exercise, but did complete the component orientation assessments. A summary of the tasks undertaken by each group of participants is outlined in table 7-1.

Table 7-1: Summary of tasks undertaken by each group of participants.

Participant	MCQ	Templating	Skin marking	Component orientation
Consultants	**X**	✓	✓	✓
Fellows	✓	✓	✓	✓
Specialty Registrars	✓	✓	✓	✓
Medical students	**X**	**X**	**X**	✓

Outcomes and statistical analysis

The outcome for the MCQ is the participants score, and their pass/fail status as determined using a pass mark of 14, which was established using the modified Angoff methodology. Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed in the pass rate between the StR and fellow groups, and the Wilcoxon rank sum test with continuity correction (Mann-Whitney test) is used to determine any significant differences observed in the MCQ score between the StR and fellow groups. The outcome for the templating task is the component size for a cemented and uncemented femoral stem, and uncemented acetabular cup selected by each participant. The acceptable range for component sizes are within the size range templated by consultants. (219, 221) Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed in the

templating sizes between consultant, fellow, and StR groups. The outcome measure for the skin marking task is the length and curvature of planned incision used for each surgical approach in centimetres. Normality of data was not assumed. Descriptive statistics and the non-parametric Kruskal-Wallis test are used to determine any significant differences in the outcome parameters between the consultant, fellow, and StR groups. Post-hoc pairwise multiple comparison analysis using Dunn's test was performed if any significant differences between groups are identified. The outcome recorded for the femur component orientation model is the stem version achieved by each participant and variance from the target 15° anteversion. Normality of data was not assumed. Descriptive statistics and the non-parametric Kruskal-Wallis rank sum test is used to determine any significant differences between groups, with a post-hoc Dunn's test if any significant differences between groups are identified. The stem version is used to categorise each participants variation from the target. Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed in the femoral stem version categories between consultant, fellow, and StR groups. The outcome for the acetabular cup orientation model is the operative inclination (OI) and anteversion (OA) achieved by each participant, and variance from the targets of 40° and 20° respectively. Normality of data was not assumed. Descriptive statistics and the non-parametric Kruskal-Wallis rank sum test is used to determine any significant differences between the consultant, fellow, and StR groups. Dunn's test was performed if any significant differences between groups were identified. The acetabular cup OI and OA readings are used to categorise each participants performance in relation to their deviation from the target. Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed in the acetabular cup OI and OA categories between consultant, fellow, and StR groups. Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The significance threshold was set at 0.05 for all statistical analysis, and data visualisation is only presented for significant findings.

7.2.3 Results

A total of 53 participants were recruited between September 2019 and June 2021, which included 3 consultant orthopaedic hip surgeons, 9 senior clinical fellows, 34 StRs, and 7 medical students.

7.2.3.1 Cognitive performance

Multiple choice questionnaire (MCQ)

All 9 senior clinical fellows and 34 StRs completed the MCQ. Between both groups, the overall median average score was 12/20 (60%, IQR 10-14), with a median average of 11/20 (55%, IQR 10-13) in the StR group and 13/20 (65%, IQR 11-15) in the fellow group (p= 0.12). Using a threshold of 14 as the pass mark, overall, 11/43 participants passed (25.6%), with 7/34 StRs (20.6%) and 4/9 fellows (55.6%) (χ^2= 0.2).

Table 7-2: Summary MCQ results.

Multiple choice questionnaire				
Variable	**Overall**, N = 43[1]	**Fellow**, N = 9[1]	**Registrar**, N = 34[1]	**p-value**[2]
MCQ score	11 (10, 14)	12 (11, 15)	11 (10, 13)	0.12
MCQ outcome				0.2
Fail	32 (74.4%)	5 (55.6%)	27 (79.4%)	
Pass	11 (25.6%)	4 (44.4%)	7 (20.6%)	

[1] Median (IQR); n (%)

[2] Wilcoxon rank sum test; Fisher's exact test

Component templating

All three consultant orthopaedic hip surgeons, nine senior clinical fellows and 34 StRs completed the component templating task. No significant differences were observed between participant groups regarding the templated cemented stem size (χ^2= 0.8), offset (χ^2= 0.8), neck length (χ^2= >0.9); uncemented acetabular cup size (χ^2= >0.9); uncemented stem size (χ^2= 0.8), offset (χ^2= 0.4), and neck length (χ^2= 0.5). Using the consultants templated size range as an indicator of acceptable templating performance: 6/9 (67%) fellows and 22/34 (65%) of StRs appropriately templated the size of a cemented femoral stem (χ^2= 0.6), 5/9 (56%) fellows and 18/34 (53%) of StRs appropriately templated the offset of a cemented femoral stem (χ^2= 0.4), 9/9 (100%) fellows and 30/34 (88%) of StRs appropriately templated the neck length of a cemented femoral stem (χ^2= 0.7), 4/9 (44%) fellows and 21/34 (62%) of StRs appropriately templated the size of an uncemented acetabular cup (χ^2= 0.3), 6/9 (67%) fellows and 20/34 (59%) of StRs appropriately templated the size of an uncemented femoral stem (χ^2= 0.6), 6/9 (67%) fellows and 28/34 (82%) of StRs appropriately templated the offset of an uncemented femoral stem (χ^2= 0.4), 5/9 (56%) fellows and 23/34 (68%) of StRs appropriately templated the neck length of an uncemented femoral stem (χ^2= 0.7).

Table 7-3: Summary component templating results.

Component templating					
Variable	**Overall**, N = 46[1]	**Consultant**, N = 3[1]	**Fellow**, N = 9[1]	**Registrar**, N = 34[1]	**p-value**[2]
Cemented stem size					0.8
1	2 (4.3%)	0 (0%)	0 (0%)	2 (5.9%)	
2	15 (33%)	1 (33%)	2 (22%)	12 (35%)	
3	16 (35%)	2 (67%)	4 (44%)	10 (29%)	
4	13 (28%)	0 (0%)	3 (33%)	10 (29%)	
Cemented stem offset					0.8
38	15 (33%)	0 (0%)	3 (33%)	12 (35%)	
45	26 (57%)	3 (100%)	5 (56%)	18 (53%)	
50	5 (11%)	0 (0%)	1 (11%)	4 (12%)	
Cemented stem neck					>0.9
-4	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
0	30 (65%)	2 (67%)	7 (78%)	21 (62%)	
4	12 (26%)	1 (33%)	2 (22%)	9 (26%)	
8	3 (6.5%)	0 (0%)	0 (0%)	3 (8.8%)	
Uncemented cup size					>0.9
48	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
50	3 (6.5%)	0 (0%)	1 (11%)	2 (5.9%)	
52	6 (13%)	0 (0%)	2 (22%)	4 (12%)	
54	10 (22%)	2 (67%)	1 (11%)	7 (21%)	
56	18 (39%)	1 (33%)	3 (33%)	14 (41%)	
58	5 (11%)	0 (0%)	2 (22%)	3 (8.8%)	
60	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
62	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
66	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
Uncemented stem size					0.8
3	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
4	1 (2.2%)	0 (0%)	0 (0%)	1 (2.9%)	
5	3 (6.5%)	0 (0%)	1 (11%)	2 (5.9%)	
6	10 (22%)	0 (0%)	2 (22%)	8 (24%)	
7	22 (48%)	1 (33%)	5 (56%)	16 (47%)	
8	7 (15%)	2 (67%)	1 (11%)	4 (12%)	
9	2 (4.3%)	0 (0%)	0 (0%)	2 (5.9%)	
Uncemented stem offset					0.4
lat	9 (20%)	0 (0%)	3 (33%)	6 (18%)	
std	37 (80%)	3 (100%)	6 (67%)	28 (82%)	
Uncemented stem neck					0.5
-4	3 (6.5%)	0 (0%)	2 (22%)	1 (2.9%)	
0	31 (67%)	3 (100%)	5 (56%)	23 (68%)	
4	9 (20%)	0 (0%)	2 (22%)	7 (21%)	
8	3 (6.5%)	0 (0%)	0 (0%)	3 (8.8%)	
Cemented stem size acceptable range	31 (67%)	3 (100%)	6 (67%)	22 (65%)	0.6
Cemented stem offset acceptable range	26 (57%)	3 (100%)	5 (56%)	18 (53%)	0.4
Cemented stem neck acceptable range	42 (91%)	3 (100%)	9 (100%)	30 (88%)	0.7
Uncemented cup size acceptable range	28 (61%)	3 (100%)	4 (44%)	21 (62%)	0.3
Uncemented stem size acceptable range	29 (63%)	3 (100%)	6 (67%)	20 (59%)	0.6
Uncemented stem offset acceptable range	37 (80%)	3 (100%)	6 (67%)	28 (82%)	0.4
Uncemented stem neck acceptable range	31 (67%)	3 (100%)	5 (56%)	23 (68%)	0.6

[1] n (%)

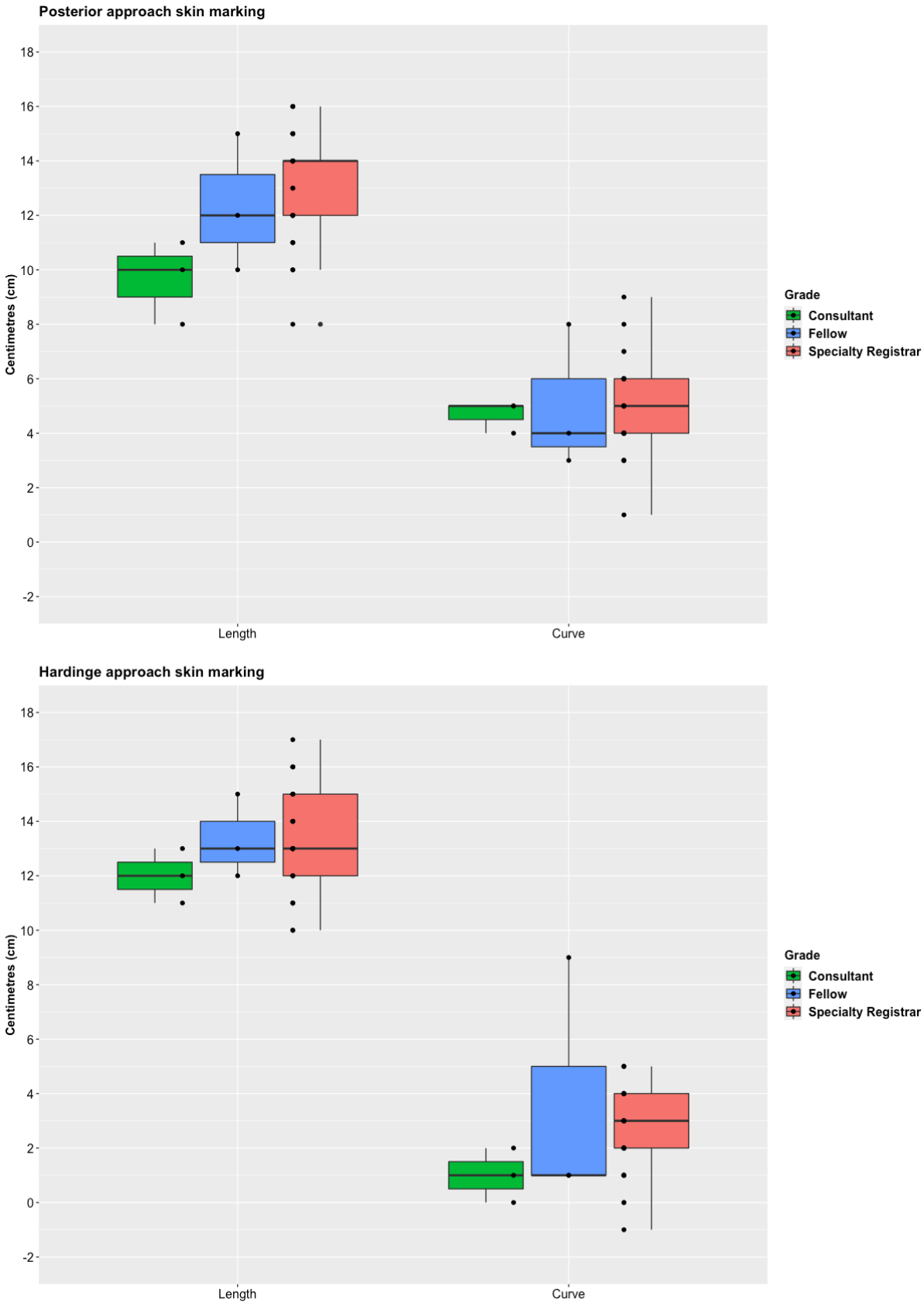
[2] Fisher's exact test

7.2.3.2 Technical skills performance

Skin marking

All three consultant orthopaedic hip surgeons, nine senior clinical fellows and 34 StRs completed the skin incision marking task. For the simulated posterior surgical approach skin marking task the median average and IQR for incision length and curvature was 10cm (IQR 1.5cm) and 5cm (IQR 0.5cm) for consultants; 12cm (IQR 2.5cm) and 4cm (IQR 2.5cm) for fellows; and 14cm (IQR 2cm) and 5cm (IQR 2cm) for StRs. Significant differences between participant groups were observed for the marked length of incision ($p= 0.04$) but not curvature ($p= 0.94$) for simulated posterior surgical approach. Dunn's test identified a significant difference between the consultant and StR groups with respect to the length of incision (adjusted $p= 0.04$), but not between any other pairwise groups. For the simulated Hardinge surgical approach skin marking task the median average and IQR for incision length and curvature was 12cm (IQR 1cm) and 1cm (IQR 1cm) for consultants; 13cm (IQR 1.5cm) and 1cm (IQR 4cm) for fellows; and 13cm (IQR 3cm) and 3cm (IQR 2cm) for StRs. No significant differences were observed between participant groups for the marked length of incision ($p= 0.34$) or curvature ($p= 0.22$) for the simulated Hardinge surgical approach.

Figure 7-3: Boxplots showing summary skin incision marking results.



Component orientation

The femoral stem orientation task was completed by two consultant orthopaedic hip surgeons, five senior clinical fellows and 22 StRs and seven medical students. The reason that all participants did not complete this task is because the methodology used for the femur model had not been validated prior to recruiting the first cohort of participants. The overall median femoral stem version (FSV) was 11.0° (IQR 8.5°), which was 4° less than the target of 15° (tables 7-4/5). No statistically significant differences in FSV were found between the four participant groups (p= 0.51). Both consultants achieved FSV within +/-5° of the target, in comparison to 40% of fellows, 64% of StRs, and 57% of medical students (χ^2= 0.7).

The acetabular cup orientation tasks were completed by all three consultant orthopaedic hip surgeons, nine senior clinical fellows, 34 StRs and seven medical students. The median average OI and OA across all participant groups and all pelvis models used in this study was 40.9° (IQR 38.6°-42.6°) and 24.8° (IQR 21.9°-29.8°), respectively. No significant differences were found in the median average OI between participant groups (p=0.15). Significant differences were found in the median average OA between participant groups (p=0.035). Pairwise group comparisons revealed this difference was due to significantly higher OA in the fellow group in comparison to the StR group (difference 5.7°, 95% CI 10.6-0.9°). There were no significant differences in the median average OI or OA between consultants and any other group. However, significant differences were observed in both OI and OA between groups in relation to the specific simulated pelvis model used in this study. No significant differences in OI or OA were found between the four participant groups using the level synthetic hemipelvis model (figure 7-2) without the MAG (p=0.4 and p=0.14, respectively). However, when using the MAG on this model StRs demonstrated a significantly increased OI in comparison to medical students (KW test p=0.032, Dunn's test p=0.04), and a significantly decreased OA in comparison to consultants (KW test p=0.011, Dunn's test p=0.04) (table 7-4 and figure 7-4). No significant differences in OI or OA were found between the four participant groups using the tilted synthetic hemipelvis model without the MAG (p=0.4 and p=0.2, respectively). When using the tilted synthetic hemipelvis model with the MAG, significant differences in OA alone were

observed between the StR and fellow groups (KW test p= 0.004), with StRs demonstrating lower OA angles than fellows (Dunn's test p=0.02) (table 7-4 and figure 7-5). No significant differences in OI or OA were found between the four participant groups using the level synthetic hemipelvis with simulated soft tissues and without the MAG (p=0.1 and p=0.7, respectively). When using the level synthetic hemipelvis with simulated soft tissues and the MAG, significant differences in OI and OA were observed between the StR and fellow groups (KW test p=0.04 and p=0.002, respectively) with StRs demonstrating higher OI and lower OA angles than fellows (Dunn's test p=0.05 and p=0.004, respectively) (table 7-4 and figure 7-6). Significantly lower OA readings were also observed in the StR group in comparison to the fellows when using the tilted synthetic hemipelvis with simulated soft tissues both with and without the MAG (Dunn's test p=0.03 and p=0.03, respectively) (table 7-4, and figures 7-7/8). A high degree of variability was observed in the participants proximity to achieving the target acetabular cup orientation (40° OI and 20° OA). Overall consultants demonstrated lower median OI in comparison to StRs in 7 out of 8 models (87.5%), and higher median OA in comparison to StRs in all models (table 7-5). Consultants achieved OI within 5° of the targets in 17 out of 24 readings (71%), which was like fellows (51 out of 72, or 71%), StRs (193 out of 272, or 71%), and medical students (40 out of 56, or 71%) (table 7-6). No significant differences were observed between the participant groups in the proximity to target OI using any of the eight models. Consultants tended to overestimate OA, with only 4 out of 24 (17%) of readings within 5° of the targets in models (table 7-6). This was in comparison to 17 out of 72 (24%) in the fellows, 143 out of 272 (53%) in the StRs, and 30 out of 56 (54%) in the medical student groups (table 7-7). Consultants most often achieved OA 10-15° higher than the target 20° (table 7-7). Significant differences were observed between the participant groups in the proximity to target OA when using: the hemipelvis model and MAG (χ^2= 0.028); the tilted hemipelvis model with the MAG (χ^2= 0.018); the hemipelvis model with simulated soft tissues and MAG (χ^2= 0.025); and the tilted hemipelvis model with simulated soft tissues and MAG (χ^2= 0.015).

Table 7-4: Summary component orientation readings from simulated tasks.

Component orientation readings						
Variable	**Overall**, N = 53[1]	**Consultant**, N = 3[1]	**Fellow**, N = 9[1]	**Registrar**, N = 34[1]	**Medical Student**, N = 7[1]	**p-value**[2]
Femur model						
Femoral stem version	11.0 (7.0, 15.5)	12.8 (11.4, 14.1)	15.0 (9.0, 20.0)	10.7 (5.5, 14.5)	15.0 (7.5, 16.0)	0.5
Unknown	17	1	4	12	0	
Hemi-pelvis model freehand						
OI	41.0 (36.7, 44.7)	36.2 (36.2, 42.6)	38.9 (36.7, 42.1)	42.1 (38.0, 45.3)	35.7 (33.2, 45.0)	0.4
OA	30.3 (26.3, 34.7)	36.3 (34.8, 41.1)	30.3 (27.5, 34.5)	29.8 (26.5, 34.0)	20.1 (17.6, 33.2)	0.14
Hemi-pelvis model and MAG						
OI	42.1 (38.7, 44.4)	38.3 (37.6, 42.0)	42.1 (37.3, 43.2)	43.5 (41.0, 44.7)	38.2 (37.0, 39.9)	**0.032**
OA	23.3 (20.1, 27.5)	33.1 (31.1, 33.2)	28.2 (23.3, 35.0)	21.8 (19.4, 24.9)	24.1 (21.8, 28.7)	**0.011**
Tilted hemi-pelvis model freehand						
OI	38.8 (36.9, 43.8)	41.9 (37.2, 45.8)	37.8 (34.8, 39.8)	39.9 (37.7, 44.4)	37.9 (37.3, 39.6)	0.4
OA	25.1 (20.3, 30.3)	30.2 (25.8, 34.2)	30.3 (28.0, 34.3)	24.8 (19.2, 28.3)	23.1 (21.9, 27.1)	0.2
Tilted hemi-pelvis model and MAG						
OI	41.3 (38.2, 44.1)	41.7 (40.0, 46.8)	39.4 (36.0, 39.8)	41.8 (39.0, 44.9)	39.3 (32.9, 42.1)	0.077
OA	22.3 (18.3, 28.1)	28.1 (27.3, 31.2)	29.7 (25.3, 34.0)	20.8 (17.0, 24.4)	23.3 (20.8, 27.4)	**0.004**
Hemi-pelvis with muscle model freehand						
OI	41.5 (38.4, 45.1)	37.5 (35.5, 39.5)	38.8 (34.0, 42.0)	42.1 (39.2, 46.9)	41.4 (40.2, 44.4)	0.10
OA	32.1 (24.4, 36.0)	31.5 (28.0, 35.3)	34.1 (31.0, 41.3)	28.4 (24.4, 35.9)	33.3 (25.3, 34.8)	0.7
Hemi-pelvis with muscle model and MAG						
OI	40.8 (38.7, 43.1)	37.3 (37.0, 39.8)	37.1 (33.7, 42.0)	41.6 (39.1, 44.8)	40.9 (40.7, 41.9)	**0.040**
OA	24.5 (21.0, 28.0)	27.4 (26.9, 30.2)	31.0 (28.0, 33.0)	22.3 (20.1, 26.2)	24.5 (22.1, 30.2)	**0.002**
Tilted hemi-pelvis with muscle model freehand						
OI	40.5 (37.4, 45.5)	37.4 (36.1, 40.4)	39.8 (36.8, 40.5)	41.2 (39.0, 46.0)	38.3 (37.5, 47.2)	0.2
OA	25.1 (20.5, 32.0)	33.0 (27.2, 33.0)	32.0 (28.3, 38.2)	24.1 (19.1, 28.1)	24.3 (20.5, 27.6)	**0.035**
Tilted hemi-pelvis with muscle model and MAG						
OI	40.7 (37.4, 43.8)	41.0 (39.4, 41.1)	37.4 (35.0, 40.7)	41.1 (37.7, 44.4)	39.6 (38.3, 42.8)	0.3
OA	21.6 (18.4, 26.2)	25.5 (25.2, 25.9)	30.5 (23.4, 32.2)	20.8 (18.2, 24.2)	21.5 (18.4, 25.6)	**0.022**
Summary figures for all acetabular cup orientation models						
OI	40.9 (38.6, 42.6)	38.4 (37.4, 42.0)	39.7 (35.5, 41.5)	41.4 (39.6, 44.3)	40.9 (38.7, 41.8)	0.15
OA	24.8 (21.9, 29.8)	32.2 (29.8, 32.3)	30.7 (28.3, 34.6)	24.3 (21.9, 26.7)	22.7 (22.0, 28.4)	**0.035**

[1] Median (IQR)

[2] Kruskal-Wallis rank sum test

Table 7-5: Summary component orientation variation from target during simulated tasks.

Component orientation variation from target						
Variable	**Overall**, N = 53[1]	**Consultant**, N = 3[1]	**Fellow**, N = 9[1]	**Registrar**, N = 34[1]	**Medical Student**, N = 7[1]	**p-value**[2]
Femur model						
Femoral stem version	-4.0 (-8.0, 0.5)	-2.2 (-3.6, -0.9)	0.0 (-6.0, 5.0)	-4.3 (-9.5, -0.5)	0.0 (-7.5, 1.0)	0.5
Unknown	17	1	4	12	0	
Hemi-pelvis model freehand						
OI	1.0 (-3.3, 4.7)	-3.8 (-3.8, 2.6)	-1.1 (-3.3, 2.1)	2.1 (-2.0, 5.3)	-4.3 (-6.8, 4.9)	0.4
OA	10.3 (6.3, 14.7)	16.3 (14.8, 21.1)	10.3 (7.5, 14.5)	9.8 (6.5, 14.0)	0.1 (-2.4, 13.2)	0.14
Hemi-pelvis model and MAG						
OI	2.1 (-1.3, 4.4)	-1.7 (-2.4, 1.9)	2.1 (-2.7, 3.2)	3.5 (1.1, 4.7)	-1.8 (-3.0, -0.1)	**0.032**
OA	3.3 (0.1, 7.5)	13.1 (11.2, 13.2)	8.2 (3.3, 15.0)	1.8 (-0.6, 4.9)	4.1 (1.8, 8.7)	**0.011**
Tilted hemi-pelvis model freehand						
OI	-1.2 (-3.1, 3.8)	1.9 (-2.8, 5.8)	-2.2 (-5.2, -0.2)	-0.1 (-2.3, 4.4)	-2.1 (-2.7, -0.4)	0.4
OA	5.1 (0.3, 10.3)	10.2 (5.8, 14.2)	10.3 (8.0, 14.3)	4.8 (-0.8, 8.3)	3.1 (1.8, 7.2)	0.2
Tilted hemi-pelvis model and MAG						
OI	1.3 (-1.8, 4.1)	1.7 (0.0, 6.8)	-0.6 (-4.0, -0.2)	1.8 (-1.0, 4.9)	-0.7 (-7.1, 2.1)	0.077
OA	2.3 (-1.7, 8.1)	8.1 (7.3, 11.2)	9.7 (5.3, 14.0)	0.8 (-3.0, 4.5)	3.3 (0.8, 7.4)	**0.004**
Hemi-pelvis with muscle model freehand						
OI	1.5 (-1.6, 5.1)	-2.5 (-4.5, -0.5)	-1.2 (-6.0, 2.0)	2.1 (-0.8, 6.9)	1.4 (0.2, 4.4)	0.10
OA	12.1 (4.4, 16.0)	11.5 (8.0, 15.3)	14.1 (11.0, 21.3)	8.4 (4.4, 15.9)	13.3 (5.3, 14.8)	0.7
Hemi-pelvis with muscle model and MAG						
OI	0.8 (-1.3, 3.1)	-2.7 (-3.0, -0.2)	-2.9 (-6.3, 2.0)	1.6 (-0.9, 4.8)	0.9 (0.7, 1.9)	**0.040**
OA	4.5 (1.0, 8.0)	7.4 (6.9, 10.2)	11.0 (8.0, 13.0)	2.3 (0.1, 6.2)	4.5 (2.1, 10.2)	**0.002**
Tilted hemi-pelvis with muscle model freehand						
OI	0.5 (-2.6, 5.5)	-2.6 (-3.9, 0.4)	-0.2 (-3.2, 0.5)	1.2 (-1.0, 6.0)	-1.7 (-2.5, 7.2)	0.2
OA	5.1 (0.5, 12.0)	13.0 (7.2, 13.0)	12.0 (8.3, 18.2)	4.1 (-0.9, 8.1)	4.3 (0.5, 7.6)	**0.035**
Tilted hemi-pelvis with muscle model and MAG						
OI	0.7 (-2.6, 3.8)	1.0 (-0.6, 1.1)	-2.6 (-5.0, 0.7)	1.1 (-2.3, 4.4)	-0.4 (-1.7, 2.8)	0.3
OA	1.6 (-1.6, 6.2)	5.5 (5.2, 5.8)	10.5 (3.4, 12.2)	0.8 (-1.8, 4.2)	1.5 (-1.6, 5.6)	**0.022**
Summary figures for all acetabular cup orientation models						
OI	0.9 (-1.4, 2.6)	-1.6 (-2.6, 2.0)	-0.3 (-4.5, 1.5)	1.4 (-0.4, 4.3)	0.9 (-1.3, 1.8)	0.15
OA	6.9 (3.3, 11.3)	13.5 (12.3, 13.6)	10.8 (7.5, 16.4)	5.3 (3.3, 8.5)	5.0 (2.0, 9.8)	0.051

[1] Median (IQR)

[2] Kruskal-Wallis rank sum test

Table 7-6: Proximity to target acetabular cup inclination according to participant grade and simulation model.

Proximity to target acetabular cup operative inclination									
Variable	Overall[1]	OI hemipelvis freehand[1]	OI hemipelvis MAG[1]	OI tilted hemipelvis freehand[1]	OI tilted hemipelvis MAG[1]	OI hemipelvis with muscle freehand[1]	OI hemipelvis with muscle MAG[1]	OI tilted hemipelvis with muscle freehand[1]	OI tilted hemipelvis with muscle MAG[1]
Consultant									
Reading									
+/-5	17 (71%)	2 (67%)	2 (67%)	1 (33%)	2 (67%)	2 (67%)	3 (100%)	2 (67%)	3 (100%)
plus 5-10	3 (12%)	1 (33%)	1 (33%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
minus 5-10	3 (12%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	1 (33%)	0 (0%)	1 (33%)	0 (0%)
plus 10-15	1 (4.2%)	0 (0%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Fellow									
Reading									
+/-5	51 (71%)	6 (67%)	6 (67%)	6 (67%)	7 (78%)	6 (67%)	6 (67%)	7 (78%)	7 (78%)
plus 5-10	2 (2.8%)	1 (11%)	1 (11%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
minus 5-10	14 (19%)	2 (22%)	2 (22%)	2 (22%)	1 (11%)	2 (22%)	2 (22%)	2 (22%)	1 (11%)
minus 10-15	5 (6.9%)	0 (0%)	0 (0%)	1 (11%)	1 (11%)	1 (11%)	1 (11%)	0 (0%)	1 (11%)
Specialty Registrar									
Reading									
+/-5	193 (71%)	22 (65%)	29 (85%)	24 (71%)	23 (68%)	20 (59%)	28 (82%)	21 (62%)	26 (76%)
plus 5-10	40 (15%)	5 (15%)	5 (15%)	1 (2.9%)	6 (18%)	6 (18%)	5 (15%)	8 (24%)	4 (12%)
minus 5-10	14 (5.1%)	2 (5.9%)	0 (0%)	5 (15%)	1 (2.9%)	2 (5.9%)	1 (2.9%)	1 (2.9%)	2 (5.9%)
plus 10-15	20 (7.4%)	3 (8.8%)	0 (0%)	4 (12%)	3 (8.8%)	4 (12%)	0 (0%)	4 (12%)	2 (5.9%)
minus 10-15	2 (0.7%)	1 (2.9%)	0 (0%)	0 (0%)	1 (2.9%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 15-30	3 (1.1%)	1 (2.9%)	0 (0%)	0 (0%)	0 (0%)	2 (5.9%)	0 (0%)	0 (0%)	0 (0%)
Medical Student									
Reading									
+/-5	40 (71%)	2 (29%)	6 (86%)	5 (71%)	4 (57%)	5 (71%)	7 (100%)	5 (71%)	6 (86%)
plus 5-10	6 (11%)	2 (29%)	0 (0%)	1 (14%)	0 (0%)	2 (29%)	0 (0%)	0 (0%)	1 (14%)
minus 5-10	6 (11%)	2 (29%)	1 (14%)	1 (14%)	2 (29%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 10-15	2 (3.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (29%)	0 (0%)
minus 10-15	2 (3.6%)	1 (14%)	0 (0%)	0 (0%)	1 (14%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

[1] n (%)

Table 7-7: Proximity to target acetabular cup anteversion according to participant grade and simulation model.

Proximity to target acetabular cup operative anteversion									
Variable	Overall[1]	OA hemipelvis freehand[1]	OA hemipelvis MAG[1]	OA tilted hemipelvis freehand[1]	OA tilted hemipelvis MAG[1]	OA hemipelvis with muscle freehand[1]	OA hemipelvis with muscle MAG[1]	OA tilted hemipelvis with muscle freehand[1]	OA tilted hemipelvis with muscle MAG[1]
Consultant									
Reading									
+/-5	4 (17%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	1 (33%)	0 (0%)	1 (33%)	1 (33%)
plus 5-10	7 (29%)	0 (0%)	1 (33%)	0 (0%)	2 (67%)	0 (0%)	2 (67%)	0 (0%)	2 (67%)
plus 10-15	9 (38%)	1 (33%)	2 (67%)	1 (33%)	1 (33%)	1 (33%)	1 (33%)	2 (67%)	0 (0%)
plus 15-30	4 (17%)	2 (67%)	0 (0%)	1 (33%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)
Fellow									
Reading									
+/-5	17 (24%)	1 (11%)	4 (44%)	1 (11%)	2 (22%)	2 (22%)	2 (22%)	2 (22%)	3 (33%)
plus 5-10	13 (18%)	3 (33%)	1 (11%)	2 (22%)	3 (33%)	0 (0%)	2 (22%)	1 (11%)	1 (11%)
plus 10-15	25 (35%)	3 (33%)	2 (22%)	3 (33%)	3 (33%)	4 (44%)	3 (33%)	3 (33%)	4 (44%)
plus 15-30	16 (22%)	2 (22%)	2 (22%)	2 (22%)	1 (11%)	3 (33%)	2 (22%)	3 (33%)	1 (11%)
minus 15-30	1 (1.4%)	0 (0%)	0 (0%)	1 (11%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Specialty Registrar									
Reading									
+/-5	143 (53%)	5 (15%)	24 (71%)	17 (50%)	24 (71%)	10 (29%)	21 (62%)	18 (53%)	24 (71%)
plus 5-10	63 (23%)	11 (32%)	6 (18%)	10 (29%)	4 (12%)	8 (24%)	9 (26%)	9 (26%)	6 (18%)
minus 5-10	11 (4.0%)	1 (2.9%)	2 (5.9%)	0 (0%)	3 (8.8%)	0 (0%)	1 (2.9%)	1 (2.9%)	3 (8.8%)
plus 10-15	33 (12%)	10 (29%)	2 (5.9%)	6 (18%)	3 (8.8%)	6 (18%)	2 (5.9%)	4 (12%)	0 (0%)
plus 15-30	22 (8.1%)	7 (21%)	0 (0%)	1 (2.9%)	0 (0%)	10 (29%)	1 (2.9%)	2 (5.9%)	1 (2.9%)
Medical Student									
Reading									
+/-5	30 (54%)	3 (43%)	4 (57%)	5 (71%)	4 (57%)	2 (29%)	3 (43%)	4 (57%)	5 (71%)
plus 5-10	10 (18%)	1 (14%)	2 (29%)	0 (0%)	2 (29%)	1 (14%)	1 (14%)	2 (29%)	1 (14%)
minus 5-10	1 (1.8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (14%)	0 (0%)	0 (0%)
plus 10-15	10 (18%)	0 (0%)	1 (14%)	2 (29%)	1 (14%)	3 (43%)	2 (29%)	0 (0%)	1 (14%)
minus 10-15	1 (1.8%)	1 (14%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 15-30	4 (7.1%)	2 (29%)	0 (0%)	0 (0%)	0 (0%)	1 (14%)	0 (0%)	1 (14%)	0 (0%)

[1] n (%)

Figure 7-4: Boxplots and barplots showing summary acetabular cup orientation readings using a level hemi-pelvis model and MAG.

Target orientation marked with solid red line.

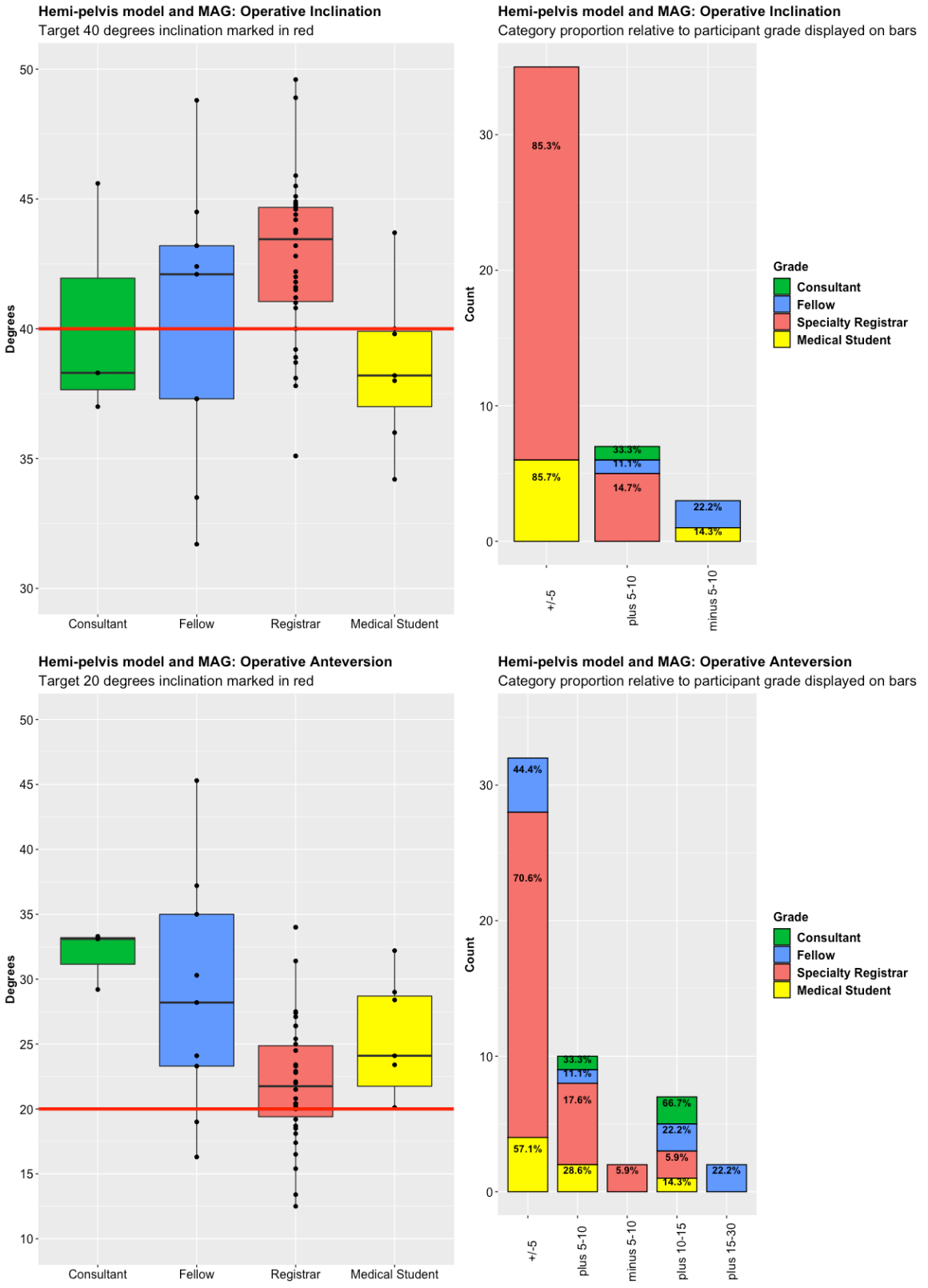


Figure 7-5: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model and MAG.

Target orientation marked with solid red line.

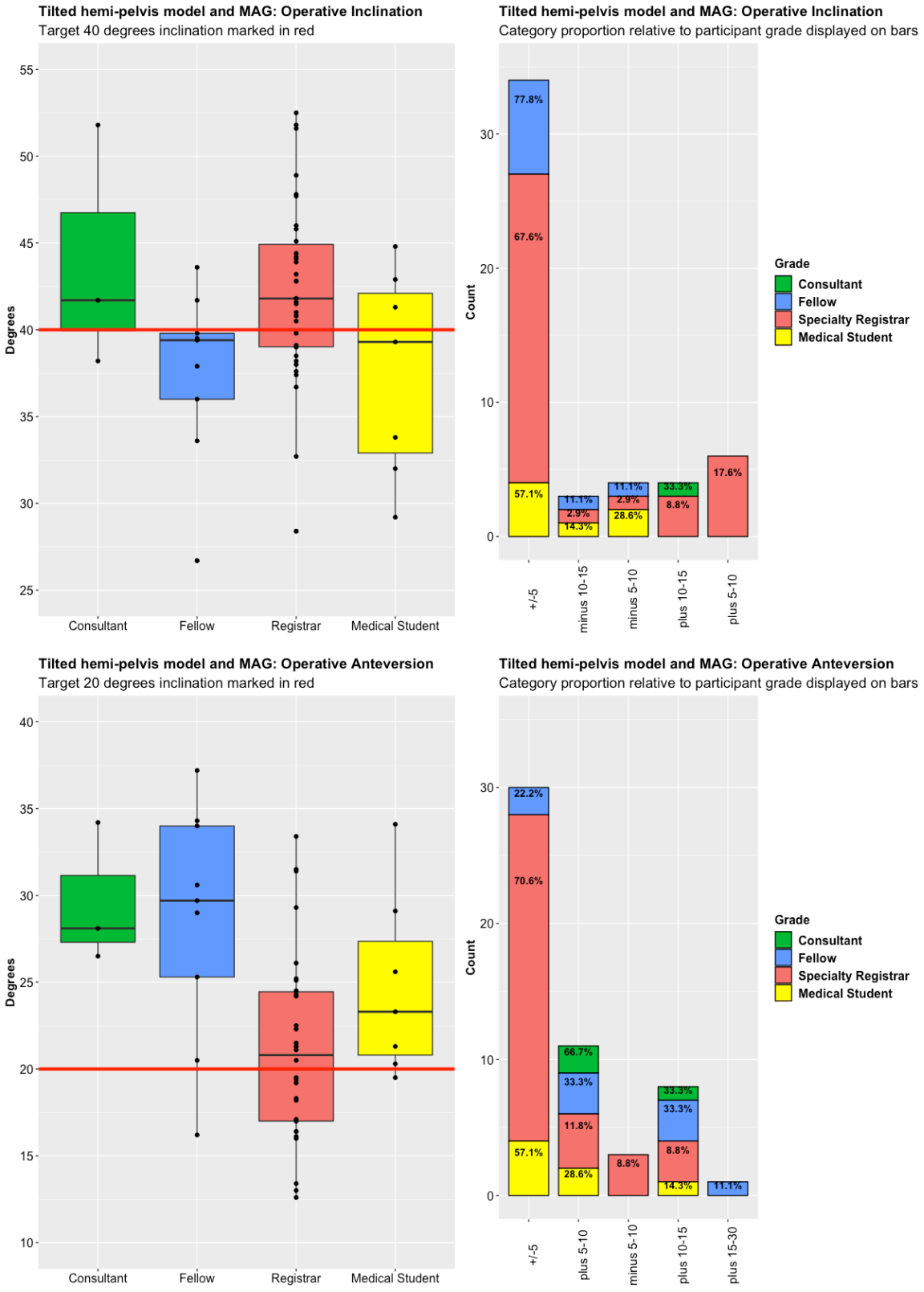


Figure 7-6: Boxplots and barplots showing summary acetabular cup orientation readings using a level hemi-pelvis model with simulated soft tissues and MAG.

Target orientation marked with solid red line.

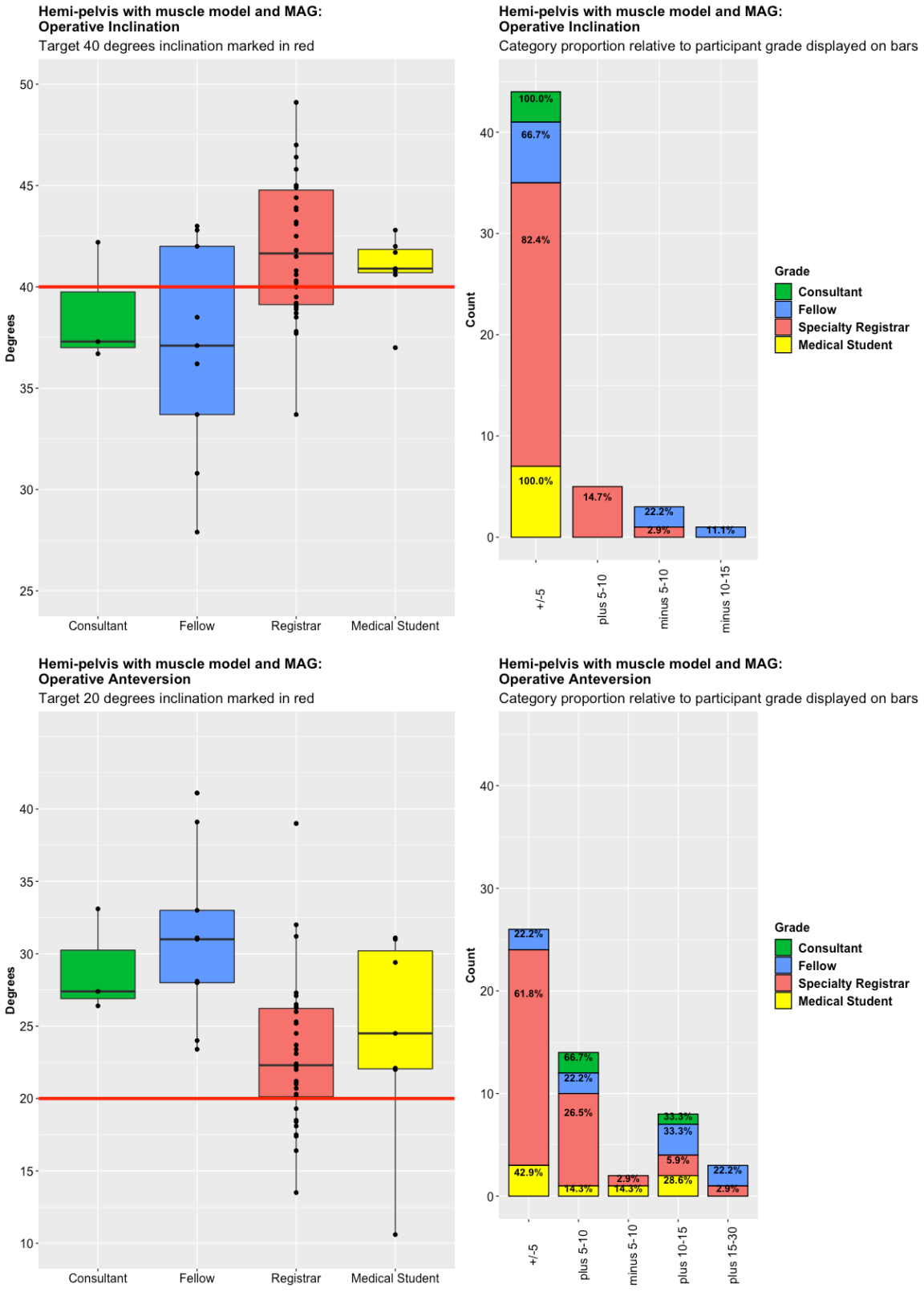


Figure 7-7: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model with simulated soft tissues without the MAG.

Target orientation marked with solid red line.

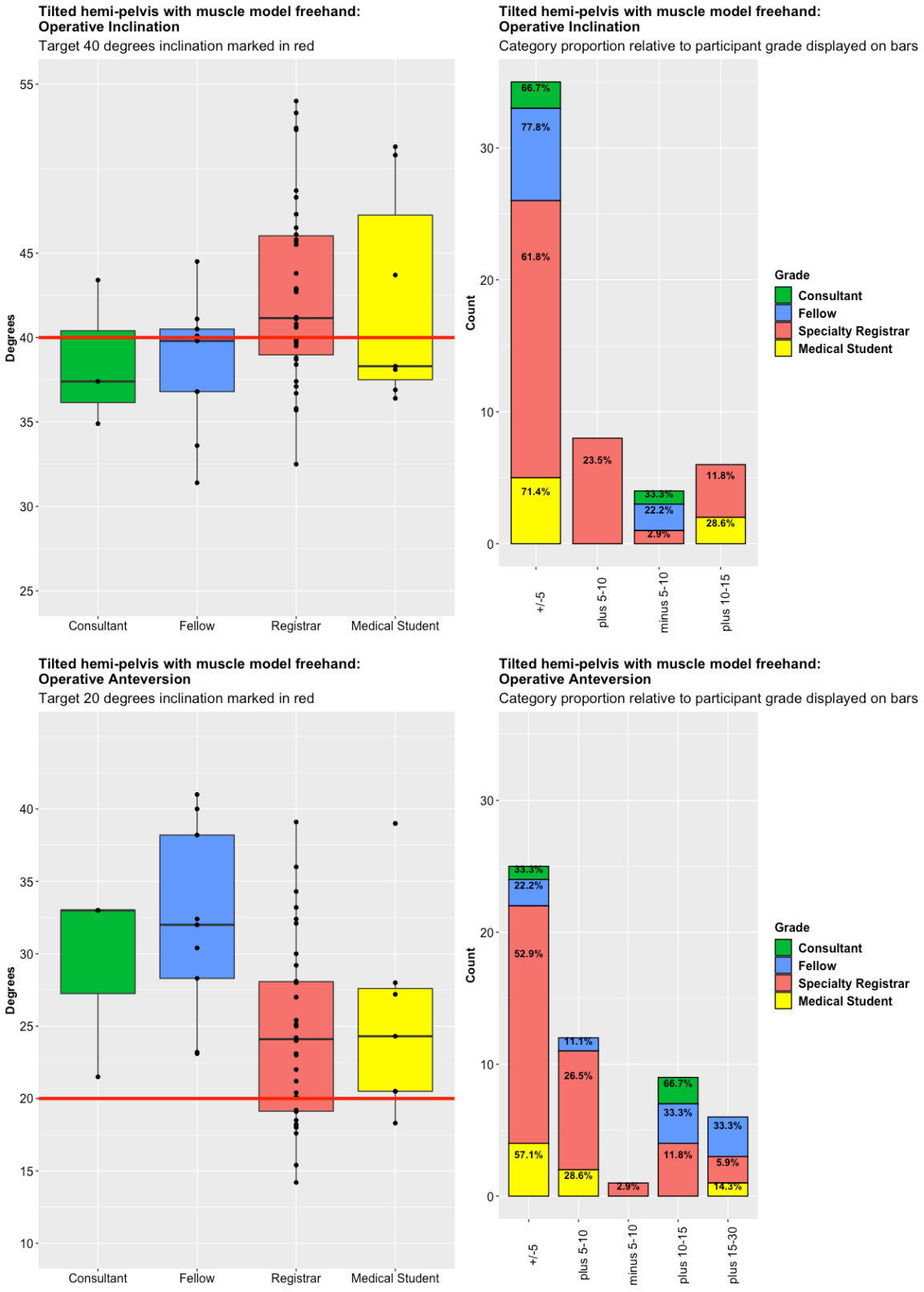
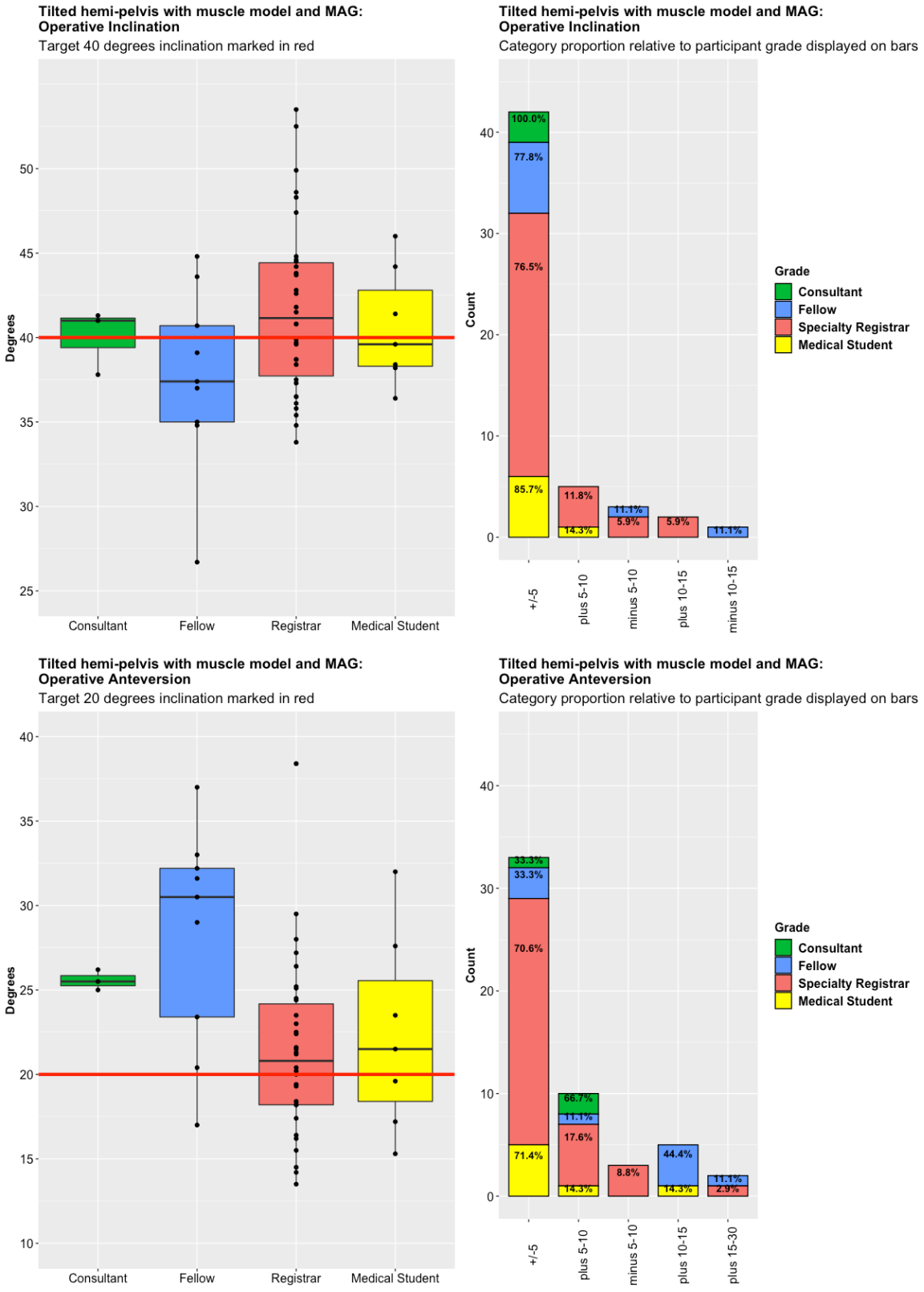


Figure 7-8: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model with simulated soft tissues and MAG.

Target orientation marked with solid red line.



7.2.4 Discussion

7.2.4.1 Summary and relevance of findings

This study has identified several differences in the performance metrics between participants in simulated aspects of THR based upon their level of experience. MCQs are an established method for assessing the cognitive performance of medical practitioners, which have been used in the field of total hip arthroplasty. (79, 246) However, neither the score or pass rate of the validated MCQ used in this study were able to differentiate between participants in the fellow and StR groups. The passing score, which was set at 14/20 (70%) by consultant hip surgeons using the modified Angoff methodology, may have been set too high to determine the 'minimally competent trainee', as only 7/34 (20.6%) StRs and 4/9 (44.4%) fellows achieved a passing score.

The component templating task was selected as studies have demonstrated a high intra- and inter-observer reliability in pre-operative THR digital templating for surgeons of varying experience levels. (247, 248) The results of this study support these previously published findings, and no significant differences were found between consultants, fellows, or StRs. The component with the largest, but statistically insignificant difference between consultant and other groups was the cemented femoral stem offset, which was undersized by 12/34 (35%) of StRs and 3/9 (33%) of fellows in comparison to consultants. This may have important implications for patient outcomes and increase the risk of complications. Reducing femoral offset has been associated with patient dissatisfaction, limp, increased joint reaction forces, and increased risk of instability and dislocation caused by a combination of inadequate abductor tension and impingement of the femoral neck on the acetabular rim on the extreme ROM. (101, 116, 119, 120, 121, 122)

The relationship between surgical grade and length of skin incision in primary THR has not been reported in a published article. The skin marking task used in this study is therefore novel and provides some insight into contemporary surgical practice. Consultants were observed to mark a significantly shorter length of skin incision than StRs, but not fellows for the posterior approach

(median 10cm, IQR 9-10.5cm vs. 14cm, IQR 12-14cm, p=0.04). There were no significant differences between groups in the curvature of the posterior or Hardinge surgical approaches, or in the length of the Hardinge approach.

The ability of surgeons to insert a femoral stem in a specified degree of anteversion during simulated THR has not previously been investigated. In this study, the overall median femoral stem anteversion (FSV) across participant groups was 11.0° (IQR 7.0-15.5°), which was 4° less than the target of 15°. Anatomical studies report a mean average native femoral neck anteversion of 11.6° across both genders. (231), but an intra-operative range of between 10-20° is acceptable. (232) The results of this study are re-assuring that most surgeons and surgical trainees are capable of accurately and consistently delivering FSV within this target range. Although no significant differences in FSV were observed between groups, it is interesting that 100% of consultants (2/2) achieved FSV within 5° of the targets, in comparison to only 40% of fellows (2/9), 64% of StRs (14/34), and 57% (4/7) of medical students.

The ability of surgeons to insert an acetabular cup in a specified orientation during simulated THR has previously been investigated and reported. (66, 78, 92, 236) Most clinical studies which report acetabular cup orientations in hip replacements use radiographic orientation readings, namely radiographic inclination (RI) and radiographic anteversion (RA). (114, 115, 117) The acetabular cup orientation readings in this study are based upon the measured operative inclination (OI) and anteversion (OA). The relationship between operative and radiographic cup orientation readings has been studied. (228, 229) The results of a study by Grammatopolous *et al* reported a mean difference between OI and RI of 5º (SD 5º), and between OA and RA of -8º (SD 8º). (229) The target acetabular cup orientation of 40° OI and 20° OA set in this study is in keeping with surgeons preferred orientations reported in other studies (66, 236), and within the 'Lewinek safe zone' of 40+/-10º RI and 15+/-10º RA (114). Within this study the median average OI and OA across all participant groups and all pelvis models used were 40.9° (IQR 38.6°-42.6°) and 24.8° (IQR 21.9°-29.8°), respectively. Consultants overestimated OA by a median average of 13.5° (IQR 12.3°-13.6°) and

underestimated OI by a median average of 1.6° (IQR -2.6°-2.0°) across all pelvic models in this study. This is less inclination error but more anteversion error than has been reported in other simulation studies. (66, 236) On average, both fellows and StRs also overestimated OA by 10.8° (IQR 7.5°-16.4°) and 5.3° (IQR 3.3°-8.5°), respectively. Although fellows underestimated OI by a median average of 0.3° (IQR -4.5°-1.5°), StRs overestimated OI by a median average of 1.4° (IQR -0.4°- 4.3°). MAG's have been shown to significantly improve acetabular cup positioning and reduce errors in comparison to freehand techniques (236, 309). Use of the MAG in all models during this study reduced the average OA readings by consultants, fellows, and StRs, which may reflect a subconscious desire of surgeons to increase anteversion in the absence of visual or mechanical cues. Overall consultants demonstrated lower median OI in comparison to StRs in 7/8 (87.5%) models, and higher median OA in comparison to StRs in all models. No significant differences were found in the median average OI between participant groups (p= 0.15), and 71% of participants from all four groups achieved OI within 5° of target. Significant differences were found in the median average OA between participant groups (p= 0.035). Pairwise group comparisons revealed this difference was due to significantly higher OA (difference 5.7°, 95% CI 10.6-0.9°) in the fellow group in comparison to the StR group. There were no significant differences in the median average OI or OA between consultants and any other group. A total of 8 scenarios for acetabular cup placement were generated using two simulated pelvis models in this study. The only model which generated significantly different results between the consultant and StR groups was the level synthetic hemipelvis model using the MAG. During this task the StRs demonstrated decreased OA in comparison to consultants (p= 0.04). Significant differences between the fellow and StR groups readings were identified using four pelvic models. StRs demonstrated lower OA angles than fellows when using the tilted synthetic hemipelvis model with the MAG (p= 0.02), and when using the tilted synthetic hemipelvis with simulated soft tissues both with and without the MAG (p= 0.03 and p= 0.03, respectively). The StR group also demonstrated higher OI and lower OA angles than fellows when using the level synthetic hemipelvis with simulated soft tissues and the MAG (p= 0.05 and p= 0.004, respectively).

Given these findings, it is evident that significant differences exist in the performance metrics between participants with varying levels of surgical experience. Although the MCQ and component templating tasks were not able to differentiate the performance of consultants, fellows, and StRs, specific aspects of the skin marking, and component orientation tasks were. Some of the key features in these simulated tasks which are associated with StRs performance, include the use of a longer skin incision for a posterior approach to the hip, and placing acetabular cups in reduced OA and increased OI in comparison to fellows and consultants. Although increasing the length of skin incision by an average of 4cm may not be detrimental to patients, altering the orientation of an acetabular cup may negatively affect patient satisfaction and outcomes following THR. The restoration of normal hip biomechanical parameters is an important aspect of THR, which is associated with improved patient function, increased component longevity, and reduced incidence of complications. (99, 100, 101, 102, 103, 104, 174, 311) Achieving this goal requires careful pre-operative radiographic analysis and component templating (200), combined with meticulous intra-operative surgical technique and judgement to prepare, and implant correctly sized components in the optimal position and orientation. This study has helped to define a normal range of values expected of both consultant orthopaedic surgeons and trainees in simulated key aspects of THR, and highlighted aspects of these tasks which are able to differentiate surgeons based upon their level of experience.

7.2.4.2 Limitations of study and future work

As the consultants participating in this study were used to validate the MCQ, they were not eligible to answer the questions. Asking an external group of consultant hip surgeons to sit this MCQ may provide an appropriate expert group against which the StR performance may be judged, as opposed to the fellow group which was used in this study. The skin marking task used in this study only allows participants to mark their planned initial incision for THR and does not account for any intra-operative extensions that are often required to gain a satisfactory exposure during a THR. Within this study participants were only invited to implant a femoral stem once, and the acetabular cup once per scenario used, with a total of eight readings per participant. Furthermore, no feedback was

provided regarding their performance in between these tasks. Theoretically, the opportunity to practice and refine component implantation with guided feedback may improve performance. However, this observational study aimed to capture a snapshot of performance with no advance ability to practice the tasks at hand. The synthetic hemipelvis models with and without simulated soft tissues lacked a transverse acetabular ligament, which is commonly used as an intra-operative aid to guide cup version. (117, 236, 269, 312) This factor should theoretically decrease the accuracy of surgeons in achieving their desired 'anatomical' acetabular cup anteversion. However, the task in this study did not require participants to recreate an anatomical cup orientation, but instead just achieve reproduce the target 40° OI and 20° OA in every scenario. Furthermore, the ability to re-test participants after a specified interval may help to determine if the knowledge and skills performance demonstrated in this study is retained and reproduceable. (276) Motion analysis assessments were not performed as part of this study and future studies may consider using commonly reported parameters such as time taken, path length, and movement counts as additional performance metrics whilst undertaking these tasks. (57, 66, 272)

7.3 Study B: Randomised controlled study assessing the impact of simulation training on performance metrics in simulated primary total hip replacement.

7.3.1 Aims

The primary aim of this study is to investigate whether a focussed simulation training module objectively improves the cognitive or technical skills performance of surgical trainees in simulated aspects of total hip replacement.

7.3.2 Methods

This is a prospective randomised controlled study. The ethical approval, location, recruitment strategy, protocol for task performance assessment, and simulation models used in this study are the same as described in study A (section 7.2). Prior to undertaking the baseline assessments all participants were invited to complete a short questionnaire aimed at capturing information relating to their training level, current operative experience and future expectations, and attendance at relevant arthroplasty courses.

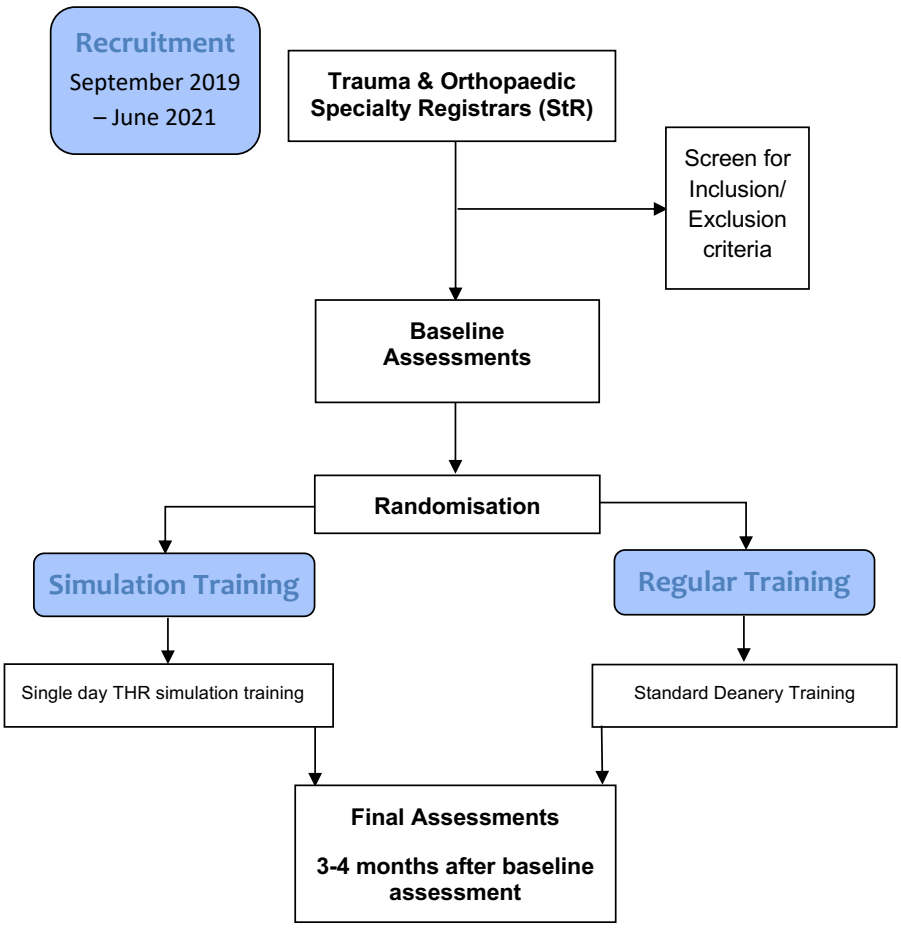
Participants and power calculation

Eligible participants were orthopaedic specialty registrars (StRs) who meet the inclusion criteria outlined in section 7.2.2. A sample size calculator was used to determine the number of participants required to power this study. (313, 314) Using an α value = 0.05, β value =0.2 a total of 16 StR participants were required in each group to detect a 20% change in MCQ score (based on a score of 11/20, IQR 2), and a 20% difference in desired acetabular cup positioning in a simulated task (based on OI 38°+/-6°, and OA 33°+/-7°). (236)

Group randomisation and timeline for assessments

The intervention to be tested in this study is the simulation-based training module outlined in chapter 5. Recruitment of StRs was undertaken at least six weeks in advance of each round of simulation-based training. In total three rounds of recruitment and simulation training were undertaken between September 2019 to June 2021. Following recruitment all participants underwent the same baseline performance assessment prior to randomisation. Randomisation of participants was performed in a 1:1 ratio using unique participant numbers in envelopes. The participants randomised to the intervention group completed the focused simulation training module delivered within a single day as described in chapter 5. Participants randomised to the control group received routine Deanery training and no additional materials. All participants were required to undertake the same follow-up assessments within 3-4 months of their baseline assessment.

Figure 7-9: Flow diagram of study design.



Outcomes and statistical analysis

Statistical analysis was performed between groups for baseline and follow-up assessments, and within the interventional (additional simulation training) group from baseline to follow-up assessments. The outcome measures for the MCQ are the participants score, and their pass/fail status as determined using a pass mark of 14. Pearson's Chi-squared test (χ^2) was used to determine any significant differences observed in the pass rate, and the Wilcoxon rank sum test with continuity correction (Mann-Whitney test) was used to determine any significant differences observed in the MCQ score. The outcome for the templating task was the component sizes for a cemented and uncemented femoral stem, and uncemented acetabular cup selected by each participant. The acceptable range for component sizes was within the size range templated by consultants in study A. Pearson's Chi-squared test (χ^2) was used to determine any significant differences observed in the templating sizes between the StR groups and the consultants. The outcome measure for the skin marking task was the length and curvature of planned incision used for each surgical approach in centimetres. Descriptive statistics and the Mann-Whitney test was used to assess differences in the outcome measures between groups. The outcome recorded for the femur component orientation model was the stem version achieved by each participant and variance from the target 15° anteversion. Pearson's Chi-squared test (χ^2) was used to determine any significant differences observed in the femoral stem version categories between groups. The outcome for the acetabular cup orientation model was the operative inclination (OI) and anteversion (OA) achieved by each participant, and variance from the targets of 40° and 20° respectively. Descriptive statistics and the Mann-Whitney test was used to assess differences in the outcome measures between groups. The acetabular cup OI and OA readings are used to categorise each participants variation from the targets. Pearson's Chi-squared test (χ^2) is used to determine any significant differences observed in the acetabular cup OI and OA categories between groups. Data analysis and visualisation were performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The significance threshold was set at 0.05 for all statistical analysis, and data visualisation is only presented for significant findings.

7.3.3 Results

A total of 34 orthopaedic StR participants were recruited in three rounds between September 2019 and June 2021. 18 participants were randomised into the intervention (additional simulation training) group, and 16 into the control (routine deanery training) group.

7.3.3.1 Participant training and operative logbook profiles

The training and surgical logbook profiles of the participants are outlined in tables 7-8/9. Overall, 30 male (88%) and 4 female (12%) participants were recruited, with no significant differences in gender observed between groups (χ^2= 0.3). Most participants were in year 4 (ST6) of the orthopaedic surgery specialty training program, with no significant differences in the year of training observed between groups (χ^2>0.9). Most participants had undertaken either 1 (12/34, 35%) or 2 (9/34, 26.5%) arthroplasty placements during their training program to date and were planning on undertaking a total of either 2 (11/34, 32%) or 3 (10/34, 29%) over the duration of their 6-year program. No significant differences were observed between groups for the number of completed (χ^2= 0.094) or planned arthroplasty placements (χ^2= 0.8). Interestingly, a significant difference was noted between groups regarding their intention to pursue a career in arthroplasty, with a greater proportion of participants in the intervention group expressing an interest in this sub-specialty (13/18 (72%) vs. 5/16 (31%), χ^2= 0.007). Only 13/34 (38%) of participants believed that the training program will meet their requirements for future clinical practice. Overall, half of all participants had not undertaken any focused courses on arthroplasty during training, and a significant difference was noted between groups with participants in the control group undertaking more courses than those in the intervention group (χ^2= 0.011). Most participants (19/34, 56%) believed that a training course in THR should be undertaken in the first year of orthopaedic specialty training (PGY1/ST3). In relation to operative numbers, 44% of participants (15/34) had performed fewer than 10 THR under supervision during their training to date, and 79% (27/34) had performed fewer than 30. There was an even spread of trainee expectations with regards to the total number of supervised THR they expected to undertake during their training program. No significant differences were observed

between groups in either the current total or expected number of supervised THR to be performed in training. An even spread of supervised performed total operative logbook numbers was observed across both groups, with 79% of trainees (27/34) expecting to perform over 1200 supervised operations by the end of their specialty training.

Table 7-8: Training profiles of recruited orthopaedic specialty registrars.

StR training profile				
Question	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
Recruitment round				>0.9
1	11 (32.4%)	6 (33.3%)	5 (31.2%)	
2	11 (32.4%)	6 (33.3%)	5 (31.2%)	
3	12 (35.3%)	6 (33.3%)	6 (37.5%)	
Gender				0.3
Female	4 (11.8%)	1 (5.6%)	3 (18.8%)	
Male	30 (88.2%)	17 (94.4%)	13 (81.2%)	
Training year				>0.9
1	4 (11.8%)	2 (11.1%)	2 (12.5%)	
2	5 (14.7%)	3 (16.7%)	2 (12.5%)	
3	3 (8.8%)	2 (11.1%)	1 (6.2%)	
4	15 (44.1%)	8 (44.4%)	7 (43.8%)	
5	4 (11.8%)	2 (11.1%)	2 (12.5%)	
6	3 (8.8%)	1 (5.6%)	2 (12.5%)	
Arthroplasty placements completed				0.094
0	7 (20.6%)	6 (33.3%)	1 (6.2%)	
1	12 (35.3%)	4 (22.2%)	8 (50.0%)	
2	9 (26.5%)	5 (27.8%)	4 (25.0%)	
3	4 (11.8%)	1 (5.6%)	3 (18.8%)	
4	2 (5.9%)	2 (11.1%)	0 (0.0%)	
Arthroplasty placements planned				0.8
1	2 (5.9%)	2 (11.1%)	0 (0.0%)	
2	11 (32.4%)	5 (27.8%)	6 (37.5%)	
3	10 (29.4%)	6 (33.3%)	4 (25.0%)	
4	6 (17.6%)	2 (11.1%)	4 (25.0%)	
5	3 (8.8%)	2 (11.1%)	1 (6.2%)	
6	2 (5.9%)	1 (5.6%)	1 (6.2%)	
Interested in arthroplasty career?				**0.007**
Yes	18 (52.9%)	13 (72.2%)	5 (31.2%)	
No	14 (41.2%)	3 (16.7%)	11 (68.8%)	
Maybe	2 (5.9%)	2 (11.1%)	0 (0.0%)	
Training sufficient for needs?				0.069
Yes	13 (38.2%)	4 (22.2%)	9 (56.2%)	
No	6 (17.6%)	3 (16.7%)	3 (18.8%)	
Maybe	15 (44.1%)	11 (61.1%)	4 (25.0%)	
Arthroplasty courses attended				**0.011**
0	17 (50.0%)	10 (55.6%)	7 (43.8%)	
1	12 (35.3%)	3 (16.7%)	9 (56.2%)	
2	5 (14.7%)	5 (27.8%)	0 (0.0%)	
Best training year for courses				0.4
1	19 (55.9%)	9 (50.0%)	10 (62.5%)	
2	11 (32.4%)	8 (44.4%)	3 (18.8%)	
3	3 (8.8%)	1 (5.6%)	2 (12.5%)	
5	1 (2.9%)	0 (0.0%)	1 (6.2%)	

[1] n (%)

[2] Pearson's Chi-squared test; Fisher's exact test

Table 7-9: Surgical logbook profiles of recruited orthopaedic specialty registrars.

StR operative logbook profile				
Question	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
THR performed supervised				0.2
0-10	15 (44.1%)	8 (44.4%)	7 (43.8%)	
11-20	6 (17.6%)	4 (22.2%)	2 (12.5%)	
21-30	6 (17.6%)	3 (16.7%)	3 (18.8%)	
31-40	2 (5.9%)	0 (0.0%)	2 (12.5%)	
41-50	2 (5.9%)	0 (0.0%)	2 (12.5%)	
>50	3 (8.8%)	3 (16.7%)	0 (0.0%)	
THR expected to be performed by end of training				0.6
21-30	3 (8.8%)	1 (5.6%)	2 (12.5%)	
31-40	9 (26.5%)	4 (22.2%)	5 (31.2%)	
41-50	10 (29.4%)	7 (38.9%)	3 (18.8%)	
>50	12 (35.3%)	6 (33.3%)	6 (37.5%)	
Total supervised logbook operations to date				0.9
0-100	3 (8.8%)	3 (16.7%)	0 (0.0%)	
101-200	3 (8.8%)	2 (11.1%)	1 (6.2%)	
201-300	3 (8.8%)	1 (5.6%)	2 (12.5%)	
301-400	2 (5.9%)	1 (5.6%)	1 (6.2%)	
401-500	2 (5.9%)	0 (0.0%)	2 (12.5%)	
501-600	5 (14.7%)	3 (16.7%)	2 (12.5%)	
601-700	4 (11.8%)	2 (11.1%)	2 (12.5%)	
701-800	4 (11.8%)	2 (11.1%)	2 (12.5%)	
801-900	2 (5.9%)	1 (5.6%)	1 (6.2%)	
901-1000	3 (8.8%)	2 (11.1%)	1 (6.2%)	
1101-1260	3 (8.8%)	1 (5.6%)	2 (12.5%)	
Expected supervised logbook operations by end of training				0.4
601-700	1 (2.9%)	1 (5.6%)	0 (0.0%)	
701-800	1 (2.9%)	1 (5.6%)	0 (0.0%)	
801-900	1 (2.9%)	1 (5.6%)	0 (0.0%)	
901-1000	2 (5.9%)	1 (5.6%)	1 (6.2%)	
1001-1100	1 (2.9%)	0 (0.0%)	1 (6.2%)	
1101-1200	1 (2.9%)	0 (0.0%)	1 (6.2%)	
1201-1300	17 (50.0%)	7 (38.9%)	10 (62.5%)	
>1301	10 (29.4%)	7 (38.9%)	3 (18.8%)	

[1] n (%)

[2] Fisher's exact test

7.3.3.2 Baseline assessment

7.3.3.2.1 Cognitive performance

Multiple choice questionnaire (MCQ)

All 34 StRs completed the baseline 'pre-course' MCQ. The overall median average score was 11/20 (IQR 3), and no significant differences were observed between groups (p>0.9). Using a threshold of 14 as the pass mark, overall, 7/34 participants passed (20.6%), and no significant differences were observed between groups (p>0.9).

Table 7-10: Summary MCQ results for the StR cohort at baseline.

Multiple choice questionnaire				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
MCQ score	11 (10, 13)	11 (10, 13)	11 (10, 13)	>0.9
MCQ outcome				>0.9
Fail	27 (79.4%)	14 (77.8%)	13 (81.2%)	
Pass	7 (20.6%)	4 (22.2%)	3 (18.8%)	

[1] Median (IQR); n (%)

[2] Wilcoxon rank sum test; Fisher's exact test

Component templating

All 34 StRs completed the baseline component templating task. No significant differences were observed between participant groups regarding the templated cemented stem size (χ^2=0.071), offset (χ^2=0.9), neck length (χ^2=0.2); uncemented acetabular cup size (χ^2=0.6); uncemented stem size (χ^2=0.8), offset (χ^2=0.7), and neck length (χ^2=0.6). Using the consultants templated size range as an indicator of acceptable performance 22/34 (65%) of StRs appropriately templated the size of a cemented femoral stem, 18/34 (53%) appropriately templated the offset of a cemented femoral stem, 30/34 (88%) appropriately templated the neck length of a cemented femoral stem (χ^2=0.039), 21/34 (62%) appropriately templated the size of an uncemented acetabular cup, 20/34 (59%) appropriately templated the size of an uncemented femoral stem, 28/34 (82%) appropriately templated the offset of an uncemented femoral stem (χ^2=0.7), and 23/34 (68%) appropriately templated the neck length of an uncemented femoral stem (χ^2=0.2). No significant differences were observed between the StR groups in relation to achieving an acceptable range of component templating for the size (χ^2=0.8) or offset (χ^2=0.7) of a cemented femoral stem; the size of the uncemented acetabular cup (χ^2>0.9); or the size (χ^2=0.3), offset (χ^2=0.7), or neck length (χ^2=0.2) of a uncemented femoral stem. A significant difference was found between StR groups in relation to the acceptable neck length selected in comparison to consultants, with 18/18 (100%) of participants in the intervention group selecting an acceptable neck length in comparison to 12/16 (75%) in the control group.

7.3.3.2.2 Technical Skills performance

Skin marking

33 StRs completed the baseline skin incision marking task. For the simulated posterior surgical approach skin marking task the median average and IQR for incision length and curvature was 14cm (IQR 2cm) and 5cm (IQR 2cm) for StRs. No significant differences were observed between participant groups for the simulated posterior surgical approach. For the simulated Hardinge surgical approach skin marking task the median average and IQR for incision length and curvature was 13cm (IQR 3cm) and 3cm (IQR 2cm) for StRs. No significant differences were observed between participant groups for the simulated Hardinge surgical approach.

Component orientation

The femoral stem orientation task was completed by 22 StRs. The overall median femoral stem version (FSV) was 10.7° (IQR 9°), which is 4.3° less than the target of 15° (tables 7-11/12). No significant differences in FSV were found between the participant groups ($p>0.9$). Overall, 14/22 (64%) of StRs achieved FSV within 5° of the targets, with no significant differences observed between the participant groups ($\chi^2>0.9$). The acetabular cup orientation tasks were completed by all 34 StRs. The median average OI and OA across both participant groups and all pelvis models used in this study was 41.4° (IQR 39.6°-44.3°) and 24.3° (IQR 21.9°-26.7°), respectively. No significant differences were found in the median average OI or OA between participant groups ($p=0.8$, and $p=0.7$, respectively). Only two significant differences were observed between groups in cup orientation angles in this study, both when using the tilted pelvis model with simulated soft tissues. The intervention group demonstrated significantly lower OA readings when using the tilted hemipelvis with simulated soft tissues without the MAG, and lower OI readings when using the tilted hemipelvis with simulated soft tissues with the MAG (tables 7-11/12, and figures 7-10/11). The only significant difference observed between groups in their categorical proximity to the target orientation was when using tilted hemipelvis with simulated soft tissues without the MAG ($\chi^2=0.002$, table 7-15). Using this model, 14/18 (78%) participants in the intervention group were within 5° of the target OA in comparison to 4/16 (25%) of participants in the control group.

Table 7-11: Summary component orientation readings for the StR cohort at baseline.

Component orientation readings				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
Femur model				
Femoral stem version	10.7 (5.5, 14.5)	11.2 (4.5, 15.1)	10.5 (7.8, 12.5)	>0.9
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	42.1 (38.0, 45.3)	42.5 (38.9, 46.8)	41.5 (37.7, 44.0)	0.5
OA	29.8 (26.5, 34.0)	28.1 (25.5, 32.2)	31.9 (27.6, 35.0)	0.10
Hemi-pelvis model and MAG				
OI	43.5 (41.0, 44.7)	43.0 (41.0, 44.2)	43.8 (41.2, 44.7)	0.6
OA	21.8 (19.4, 24.9)	22.5 (20.4, 24.9)	20.4 (19.1, 24.6)	0.6
Tilted hemi-pelvis model freehand				
OI	39.9 (37.7, 44.4)	39.9 (37.9, 44.2)	39.4 (37.2, 44.3)	0.8
OA	24.8 (19.2, 28.3)	25.6 (19.4, 28.6)	23.4 (19.1, 27.3)	0.6
Tilted hemi-pelvis model and MAG				
OI	41.8 (39.0, 44.9)	41.2 (38.1, 43.8)	43.5 (40.7, 45.8)	0.13
OA	20.8 (17.0, 24.4)	20.4 (16.5, 24.4)	20.8 (17.9, 23.0)	>0.9
Hemi-pelvis with muscle model freehand				
OI	42.1 (39.2, 46.9)	44.7 (38.8, 48.6)	40.9 (39.2, 43.7)	0.3
OA	28.4 (24.4, 35.9)	29.1 (23.4, 35.9)	28.4 (25.0, 35.6)	>0.9
Hemi-pelvis with muscle model and MAG				
OI	41.6 (39.1, 44.8)	42.5 (40.0, 44.3)	41.1 (39.1, 45.2)	>0.9
OA	22.3 (20.1, 26.2)	21.6 (20.1, 25.4)	23.9 (20.1, 26.3)	0.6
Tilted hemi-pelvis with muscle model freehand				
OI	41.2 (39.0, 46.0)	42.8 (39.0, 46.0)	41.0 (39.5, 46.2)	>0.9
OA	24.1 (19.1, 28.1)	20.8 (18.4, 24.1)	26.2 (24.3, 29.9)	**0.031**
Tilted hemi-pelvis with muscle model and MAG				
OI	41.1 (37.7, 44.4)	39.2 (36.7, 41.5)	44.0 (41.0, 45.7)	**0.017**
OA	20.8 (18.2, 24.2)	21.2 (18.6, 24.2)	20.2 (18.2, 23.5)	0.8
Summary figures for all acetabular cup orientation models				
OI	41.4 (39.6, 44.3)	41.4 (39.3, 44.3)	41.2 (40.4, 44.1)	0.8
OA	24.3 (21.9, 26.7)	24.4 (21.7, 26.6)	24.2 (22.0, 26.0)	0.7

[1] Median (IQR)

[2] Kruskal-Wallis rank sum test

Table 7-12: Summary component orientation variation from target for StR cohort at baseline.

Component orientation variation from target				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
Femur model				
Femoral stem version	-4.3 (-9.5, -0.5)	-3.8 (-10.5, 0.1)	-4.5 (-7.2, -2.5)	>0.9
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	2.1 (-2.0, 5.3)	2.4 (-1.1, 6.8)	1.6 (-2.3, 4.0)	0.5
OA	9.8 (6.5, 14.0)	8.1 (5.5, 12.2)	11.8 (7.6, 15.0)	0.10
Hemi-pelvis model and MAG				
OI	3.5 (1.1, 4.7)	3.0 (1.0, 4.2)	3.8 (1.2, 4.7)	0.6
OA	1.8 (-0.6, 4.9)	2.5 (0.4, 4.9)	0.4 (-0.9, 4.6)	0.6
Tilted hemi-pelvis model freehand				
OI	-0.1 (-2.3, 4.4)	-0.1 (-2.1, 4.2)	-0.6 (-2.8, 4.3)	0.8
OA	4.8 (-0.8, 8.3)	5.6 (-0.6, 8.6)	3.4 (-0.9, 7.3)	0.6
Tilted hemi-pelvis model and MAG				
OI	1.8 (-1.0, 4.9)	1.2 (-1.9, 3.8)	3.6 (0.7, 5.8)	0.13
OA	0.8 (-3.0, 4.5)	0.4 (-3.5, 4.5)	0.8 (-2.1, 3.0)	>0.9
Hemi-pelvis with muscle model freehand				
OI	2.1 (-0.8, 6.9)	4.7 (-1.2, 8.6)	0.9 (-0.8, 3.7)	0.3
OA	8.4 (4.4, 15.9)	9.2 (3.4, 15.9)	8.4 (5.0, 15.6)	>0.9
Hemi-pelvis with muscle model and MAG				
OI	1.6 (-0.9, 4.8)	2.4 (0.1, 4.3)	1.1 (-0.9, 5.2)	>0.9
OA	2.3 (0.1, 6.2)	1.6 (0.1, 5.4)	3.9 (0.1, 6.3)	0.6
Tilted hemi-pelvis with muscle model freehand				
OI	1.2 (-1.0, 6.0)	2.8 (-1.0, 6.0)	0.9 (-0.5, 6.2)	>0.9
OA	4.1 (-0.9, 8.1)	0.8 (-1.6, 4.1)	6.2 (4.3, 9.9)	**0.031**
Tilted hemi-pelvis with muscle model and MAG				
OI	1.1 (-2.3, 4.4)	-0.8 (-3.3, 1.5)	4.0 (1.0, 5.7)	**0.017**
OA	0.8 (-1.8, 4.2)	1.2 (-1.4, 4.2)	0.2 (-1.8, 3.5)	0.8
Summary figures for all acetabular cup orientation models				
OI	1.4 (-0.4, 4.3)	1.4 (-0.7, 4.3)	1.2 (0.4, 4.1)	0.8
OA	5.3 (3.3, 8.5)	5.0 (2.1, 8.4)	5.5 (3.7, 9.1)	0.6

[1] Median (IQR)

[2] Wilcoxon rank sum test

Table 7-13: Proximity to target acetabular cup inclination according to participant group and simulation model for the StR cohort at baseline.

Proximity to target acetabular cup operative inclination									
Variable	**Overall[1]**	**OI hemipelvis freehand[1]**	**OI hemipelvis MAG[1]**	**OI tilted hemipelvis freehand[1]**	**OI tilted hemipelvis MAG[1]**	**OI hemipelvis with muscle freehand[1]**	**OI hemipelvis with muscle MAG[1]**	**OI tilted hemipelvis with muscle freehand[1]**	**OI tilted hemipelvis with muscle MAG[1]**
Intervention									
Reading									
+/-5	102 (71%)	10 (56%)	16 (89%)	13 (72%)	12 (67%)	8 (44%)	16 (89%)	12 (67%)	15 (83%)
plus 5-10	19 (13%)	2 (11%)	2 (11%)	1 (5.6%)	2 (11%)	5 (28%)	1 (5.6%)	4 (22%)	2 (11%)
minus 5-10	7 (4.9%)	1 (5.6%)	0 (0%)	2 (11%)	1 (5.6%)	1 (5.6%)	1 (5.6%)	0 (0%)	1 (5.6%)
plus 10-15	11 (7.6%)	3 (17%)	0 (0%)	2 (11%)	2 (11%)	2 (11%)	0 (0%)	2 (11%)	0 (0%)
minus 10-15	2 (1.4%)	1 (5.6%)	0 (0%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 15-30	3 (2.1%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	2 (11%)	0 (0%)	0 (0%)	0 (0%)
Control									
Reading									
+/-5	91 (71%)	12 (75%)	13 (81%)	11 (69%)	11 (69%)	12 (75%)	12 (75%)	9 (56%)	11 (69%)
plus 5-10	21 (16%)	3 (19%)	3 (19%)	0 (0%)	4 (25%)	1 (6.2%)	4 (25%)	4 (25%)	2 (12%)
minus 5-10	7 (5.5%)	1 (6.2%)	0 (0%)	3 (19%)	0 (0%)	1 (6.2%)	0 (0%)	1 (6.2%)	1 (6.2%)
plus 10-15	9 (7.0%)	0 (0%)	0 (0%)	2 (12%)	1 (6.2%)	2 (12%)	0 (0%)	2 (12%)	2 (12%)

[1] n (%)

Table 7-14: Proximity to target acetabular cup anteversion according to participant group and simulation model for the StR cohort at baseline.

Proximity to target acetabular cup operative anteversion									
Variable	**Overall[1]**	**OA hemipelvis freehand[1]**	**OA hemipelvis MAG[1]**	**OA tilted hemipelvis freehand[1]**	**OA tilted hemipelvis MAG[1]**	**OA hemipelvis with muscle freehand[1]**	**OA hemipelvis with muscle MAG[1]**	**OA tilted hemipelvis with muscle freehand[1]**	**OA tilted hemipelvis with muscle MAG[1]**
Intervention									
Reading									
+/-5	80 (56%)	3 (17%)	11 (61%)	8 (44%)	12 (67%)	6 (33%)	13 (72%)	14 (78%)	13 (72%)
plus 5-10	28 (19%)	7 (39%)	4 (22%)	6 (33%)	2 (11%)	3 (17%)	3 (17%)	1 (5.6%)	2 (11%)
minus 5-10	8 (5.6%)	1 (5.6%)	2 (11%)	0 (0%)	2 (11%)	0 (0%)	0 (0%)	1 (5.6%)	2 (11%)
plus 10-15	16 (11%)	4 (22%)	1 (5.6%)	3 (17%)	2 (11%)	4 (22%)	1 (5.6%)	1 (5.6%)	0 (0%)
plus 15-30	12 (8.3%)	3 (17%)	0 (0%)	1 (5.6%)	0 (0%)	5 (28%)	1 (5.6%)	1 (5.6%)	1 (5.6%)
Control									
Reading									
+/-5	63 (49%)	2 (12%)	13 (81%)	9 (56%)	12 (75%)	4 (25%)	8 (50%)	4 (25%)	11 (69%)
plus 5-10	35 (27%)	4 (25%)	2 (12%)	4 (25%)	2 (12%)	5 (31%)	6 (38%)	8 (50%)	4 (25%)
minus 5-10	3 (2.3%)	0 (0%)	0 (0%)	0 (0%)	1 (6.2%)	0 (0%)	1 (6.2%)	0 (0%)	1 (6.2%)
plus 10-15	17 (13%)	6 (38%)	1 (6.2%)	3 (19%)	1 (6.2%)	2 (12%)	1 (6.2%)	3 (19%)	0 (0%)
plus 15-30	10 (7.8%)	4 (25%)	0 (0%)	0 (0%)	0 (0%)	5 (31%)	0 (0%)	1 (6.2%)	0 (0%)

[1] n (%)

Figure 7-10: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model with simulated soft tissues without the MAG for the StR cohort at baseline.

Target orientation marked with solid red line.

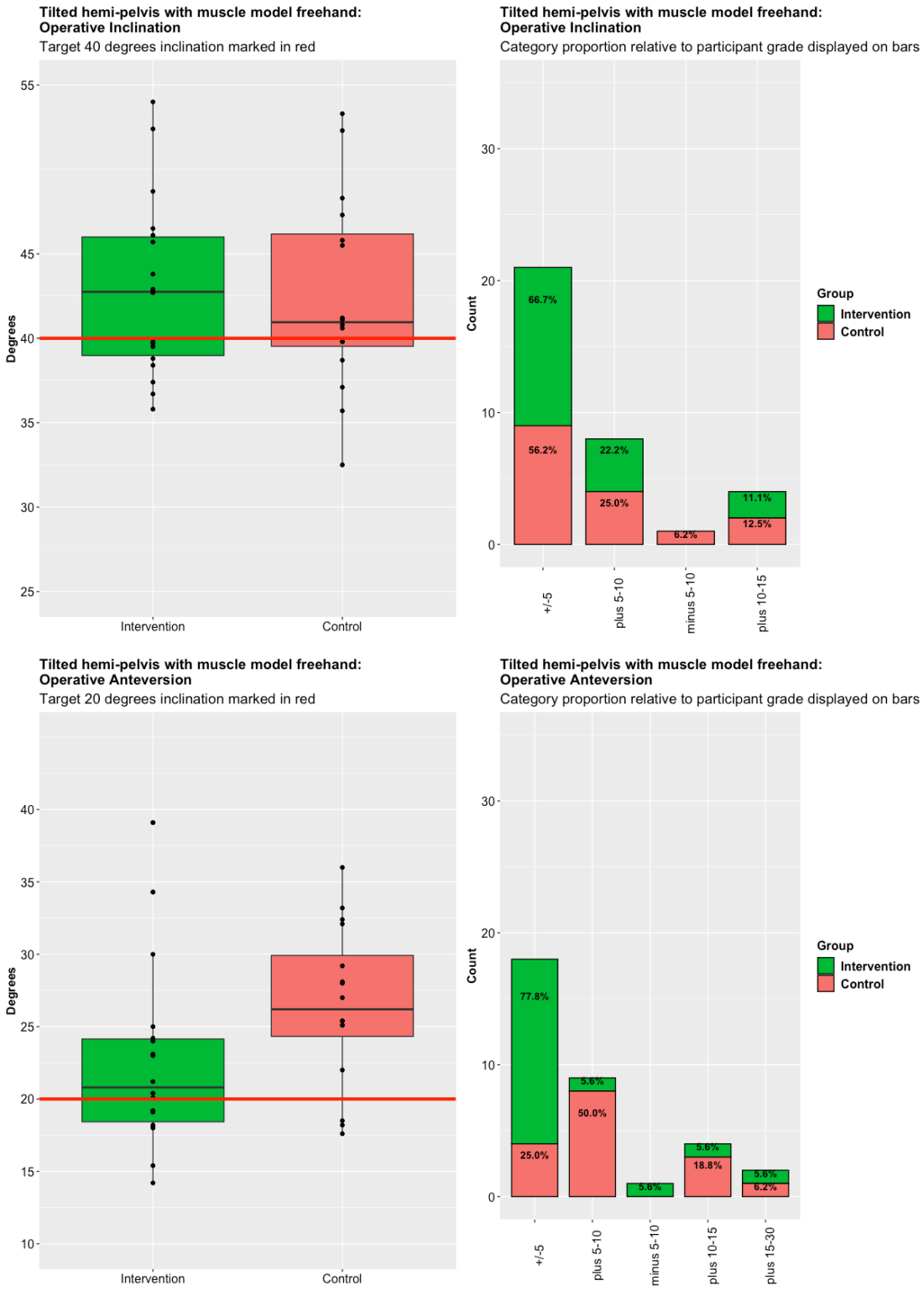
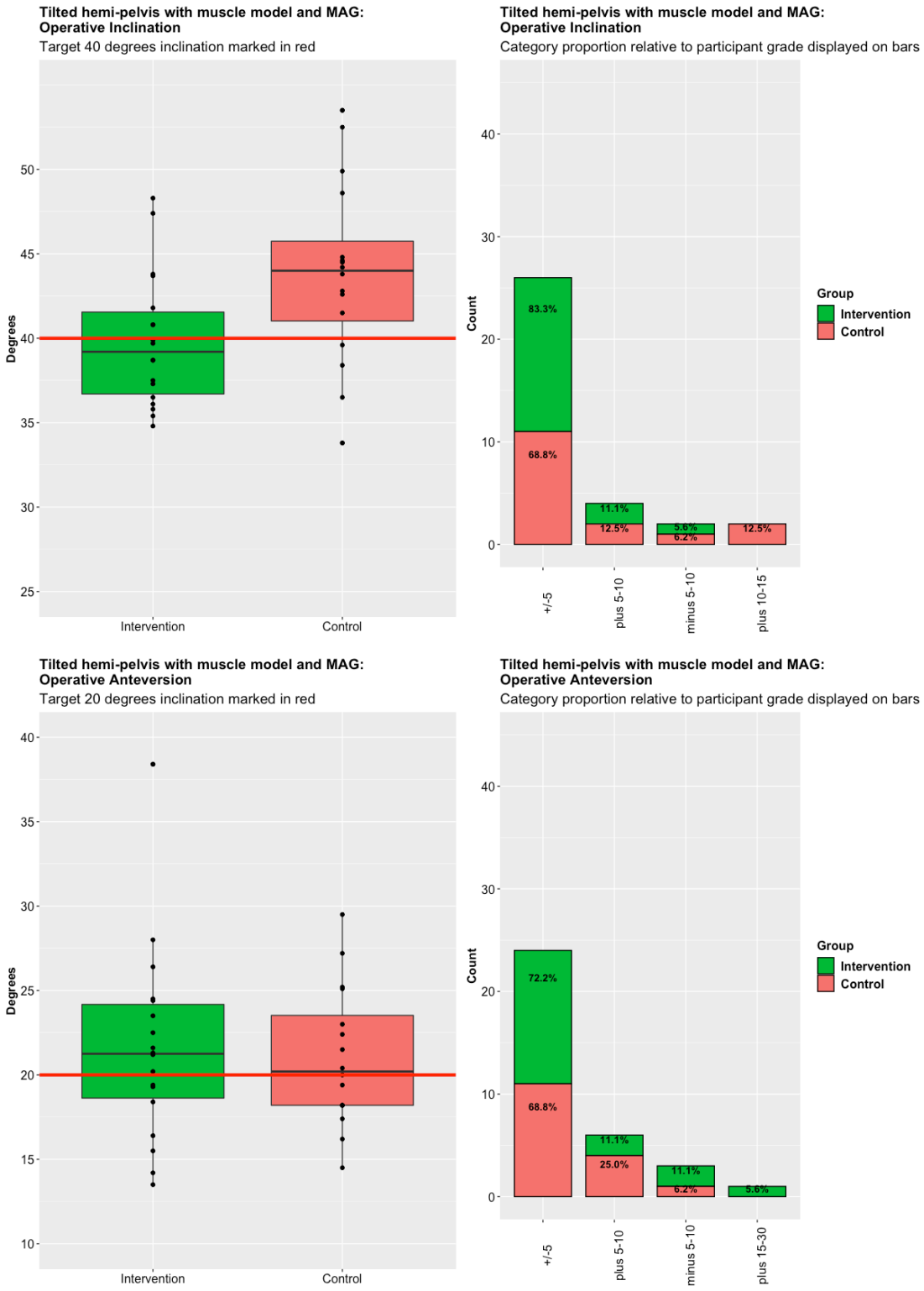


Figure 7-11: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model with simulated soft tissues and MAG for the StR cohort at baseline.

Target orientation marked with solid red line.



7.3.3.3 Follow-up assessment

Two StRs from the control group did not attend for follow-up assessments (UPN CG-205 and CG-105). Both participants were senior trainees who had taken up fellowship training posts out of area and were unable to return to the OOSEC to complete the required assessments. All participants from the intervention group completed the follow-up assessments.

7.3.3.3.1 Cognitive performance

Multiple choice questionnaire (MCQ)

Overall, 94% (32/34) of StR participants completed the follow-up MCQ. The overall median average score was 12/20 (60%, IQR 5), and no significant differences were observed in scores between groups (p=0.2). Using a threshold of 14 as the pass mark, overall, 13/34 participants passed (38.2%). Although a greater percentage of participants from the intervention group achieved a passing score in comparison to control group participants (44.4% versus 31.2%) no significant differences in pass rates were observed between groups (p=0.4).

Table 7-15: Summary MCQ results for the StR cohort at follow-up.

Multiple choice questionnaire				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
MCQ score	12 (10, 15)	12 (10, 16)	12 (9, 14)	0.2
Unknown	2	0	2	
MCQ outcome				0.4
Pass	13 (38.2%)	8 (44.4%)	5 (31.2%)	
Fail	19 (55.9%)	10 (55.6%)	9 (56.2%)	
NA	2 (5.9%)	0 (0.0%)	2 (12.5%)	

[1] Median (IQR); n (%)

[2] Wilcoxon rank sum test; Fisher's exact test

Component templating

Overall, 94% (32/34) of StR participants completed the follow-up component templating task. No significant differences were observed between participant groups regarding the templated cemented stem size (χ^2=0.9), offset (χ^2>0.9), neck length (χ^2=0.095); uncemented acetabular cup size (χ^2=0.8); uncemented stem size (χ^2=0.13), offset (χ^2=0.8), and neck length (χ^2=0.2). Using the consultants templated size range as an indicator of acceptable performance 21/32 (66%) of StRs appropriately templated the size of a cemented femoral stem, 23/32 (72%) appropriately templated the offset of a cemented femoral stem, 30/32 (90%) appropriately templated the neck length of a cemented femoral stem, 16/32 (50%) appropriately templated the size of an uncemented acetabular cup, 22/32 (69%) appropriately templated the size of an uncemented femoral stem, 28/32 (90%) appropriately templated the offset of an uncemented femoral stem, and 22/32 (69%) appropriately templated the neck length of an uncemented femoral stem. No significant differences were observed between the StR groups in relation to achieving an acceptable range of component templating for the size (χ^2=0.5), offset (χ^2>0.9), or neck length (χ^2=0.2) of a cemented femoral stem (χ^2=0.5); the size of the uncemented acetabular cup (χ^2>0.9); or the size (χ^2=0.062), offset (χ^2=0.6), or neck length (χ^2=0.4) of a uncemented femoral stem.

7.3.3.3.2 Technical Skills performance

Skin marking

Overall, 91% (31/34) of StR participants completed the follow-up skin incision marking task. For the simulated posterior surgical approach skin marking task the median average and IQR for incision length and curvature was 13cm (IQR 3cm) and 5cm (IQR 2cm) for StRs. No significant differences were observed between StR participant groups for the length (p=0.97) or curvature (p=0.78) of skin marking for the simulated posterior surgical approach. For the simulated Hardinge surgical approach skin marking task the median average and IQR for incision length and curvature was 13cm (IQR 2cm) and 3cm (IQR 2cm) for StRs. No significant differences were observed between StR participant groups for the length (p=0.74) or curvature (p=0.78) of skin marking for the simulated Hardinge surgical approach.

Component orientation

The femoral stem orientation task was completed by 22 StRs. The overall median femoral stem version (FSV) was 12.5° (IQR 5°), which is 2.5° less than the target of 15° (tables 7-16/17). No significant differences in FSV were found between the participant groups (p=0.8). Overall, 18/22 (82%) of StRs achieved FSV within 5° of the targets, with no significant differences observed between the participant groups (χ^2=0.4). The acetabular cup orientation tasks were completed by 32 StRs. The median average OI and OA across both participant groups and all pelvis models used in this study was 39.9° (IQR 38.4°-42.3°) and 24.2° (IQR 22.5°-26.1°), respectively (table 7-16). No significant differences were found in the median average OI or OA between participant groups (p=0.3 for both). Only one significant difference was observed between the groups in cup orientation angles in this study when using the level pelvis model and MAG. The control group demonstrated significantly higher OI readings than the intervention group when performing this task (p=0.046, tables 7-16/17, and figure 7-12). There were no significant differences observed between groups in their categorical proximity to the target orientation in the femur or acetabular cup orientation tasks.

Table 7-16: Summary component orientation readings for the StR cohort at follow-up.

Component orientation readings				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
Femur model				
Femoral stem version	12.5 (10.0, 15.0)	11.5 (10.0, 14.2)	13.5 (8.5, 15.0)	0.8
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	38.9 (36.9, 43.3)	39.0 (36.8, 43.4)	38.9 (37.5, 41.9)	0.8
Unknown	2	0	2	
OA	27.1 (19.0, 31.5)	25.4 (18.4, 32.8)	27.6 (21.8, 29.2)	0.9
Unknown	2	0	2	
Hemi-pelvis model and MAG				
OI	41.1 (37.9, 43.7)	39.8 (37.1, 42.5)	41.5 (41.0, 43.9)	0.15
Unknown	2	0	2	
OA	20.4 (18.0, 23.5)	19.4 (17.4, 24.3)	20.9 (19.2, 22.9)	0.6
Unknown	2	0	2	
Tilted hemi-pelvis model freehand				
OI	38.4 (34.8, 44.0)	39.9 (33.6, 44.1)	37.0 (35.2, 43.0)	0.9
Unknown	2	0	2	
OA	23.2 (19.9, 26.5)	23.4 (19.6, 29.8)	22.7 (20.6, 25.2)	0.7
Unknown	2	0	2	
Tilted hemi-pelvis model and MAG				
OI	40.1 (38.3, 43.7)	39.2 (37.8, 42.4)	43.1 (39.9, 43.8)	**0.046**
Unknown	2	0	2	
OA	20.7 (18.2, 24.3)	21.5 (18.7, 26.2)	20.6 (17.5, 22.6)	0.3
Unknown	2	0	2	
Hemi-pelvis with muscle model freehand				
OI	41.0 (38.1, 43.2)	40.8 (37.5, 42.7)	41.0 (38.8, 43.7)	0.6
Unknown	2	0	2	
OA	27.4 (24.4, 32.7)	29.9 (25.2, 35.4)	25.7 (24.3, 29.9)	0.2
Unknown	2	0	2	
Hemi-pelvis with muscle model and MAG				
OI	40.8 (38.4, 43.0)	41.7 (38.8, 43.3)	40.8 (38.3, 42.1)	0.4
Unknown	2	0	2	
OA	23.4 (21.9, 26.1)	23.8 (22.2, 25.9)	22.8 (20.6, 26.2)	0.7
Unknown	2	0	2	
Tilted hemi-pelvis with muscle model freehand				
OI	41.0 (38.2, 43.8)	40.0 (38.0, 43.5)	41.9 (40.3, 44.5)	0.2
Unknown	2	0	2	
OA	24.5 (23.2, 27.7)	25.2 (23.3, 31.7)	24.0 (23.1, 26.8)	0.3
Unknown	2	0	2	
Tilted hemi-pelvis with muscle model and MAG				
OI	41.5 (38.2, 43.0)	39.8 (37.6, 44.4)	41.8 (40.4, 42.4)	0.5
Unknown	2	0	2	
OA	22.2 (19.9, 27.1)	22.8 (20.5, 27.1)	21.6 (19.3, 26.0)	0.3
Unknown	2	0	2	
Summary figures for all acetabular cup orientation models				
OI	39.9 (38.4, 42.3)	39.1 (38.0, 42.7)	40.6 (39.4, 41.9)	0.3
Unknown	2	0	2	
OA	24.2 (22.5, 26.1)	24.6 (21.6, 27.1)	24.1 (22.9, 24.9)	0.3
Unknown	2	0	2	

[1] Median (IQR)

[2] Kruskal-Wallis rank sum test

Table 7-17: Summary component orientation variation from target for the StR cohort at follow-up.

Component orientation variation from target				
Variable	**Overall**, N = 34[1]	**Intervention**, N = 18[1]	**Control**, N = 16[1]	**p-value**[2]
Femur model				
Femoral stem version	-2.5 (-5.0, 0.0)	-3.5 (-5.0, -0.8)	-1.5 (-6.5, 0.0)	0.8
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	-1.1 (-3.1, 3.3)	-0.9 (-3.2, 3.4)	-1.1 (-2.5, 1.9)	0.8
Unknown	2	0	2	
OA	7.1 (-1.0, 11.5)	5.4 (-1.6, 12.8)	7.6 (1.7, 9.2)	0.9
Unknown	2	0	2	
Hemi-pelvis model and MAG				
OI	1.1 (-2.2, 3.7)	-0.2 (-2.9, 2.5)	1.5 (1.0, 3.9)	0.15
Unknown	2	0	2	
OA	0.3 (-2.0, 3.5)	-0.6 (-2.6, 4.3)	0.8 (-0.8, 2.9)	0.6
Unknown	2	0	2	
Tilted hemi-pelvis model freehand				
OI	-1.6 (-5.2, 4.1)	-0.1 (-6.4, 4.1)	-3.0 (-4.8, 3.0)	0.9
Unknown	2	0	2	
OA	3.2 (-0.1, 6.5)	3.3 (-0.4, 9.8)	2.7 (0.6, 5.2)	0.7
Unknown	2	0	2	
Tilted hemi-pelvis model and MAG				
OI	0.1 (-1.7, 3.7)	-0.8 (-2.2, 2.4)	3.1 (-0.1, 3.8)	**0.046**
Unknown	2	0	2	
OA	0.7 (-1.8, 4.3)	1.5 (-1.3, 6.2)	0.6 (-2.5, 2.7)	0.3
Unknown	2	0	2	
Hemi-pelvis with muscle model freehand				
OI	1.1 (-1.9, 3.2)	0.8 (-2.5, 2.7)	1.1 (-1.2, 3.7)	0.6
Unknown	2	0	2	
OA	7.4 (4.4, 12.7)	9.8 (5.2, 15.3)	5.7 (4.3, 9.9)	0.2
Unknown	2	0	2	
Hemi-pelvis with muscle model and MAG				
OI	0.8 (-1.6, 3.0)	1.7 (-1.2, 3.3)	0.8 (-1.7, 2.1)	0.4
Unknown	2	0	2	
OA	3.4 (1.9, 6.1)	3.8 (2.2, 5.9)	2.8 (0.6, 6.2)	0.7
Unknown	2	0	2	
Tilted hemi-pelvis with muscle model freehand				
OI	0.9 (-1.8, 3.8)	-0.1 (-2.0, 3.5)	1.9 (0.3, 4.5)	0.2
Unknown	2	0	2	
OA	4.5 (3.2, 7.7)	5.2 (3.3, 11.7)	4.0 (3.1, 6.8)	0.3
Unknown	2	0	2	
Tilted hemi-pelvis with muscle model and MAG				
OI	1.5 (-1.8, 3.0)	-0.2 (-2.4, 4.4)	1.8 (0.4, 2.4)	0.5
Unknown	2	0	2	
OA	2.2 (-0.1, 7.1)	2.8 (0.5, 7.1)	1.6 (-0.7, 6.0)	0.3
Unknown	2	0	2	
Summary figures for all acetabular cup orientation models				
OI	-0.1 (-1.6, 2.3)	-0.9 (-2.0, 2.7)	0.6 (-0.6, 1.9)	0.3
Unknown	2	0	2	
OA	5.4 (2.9, 6.8)	5.3 (2.3, 7.8)	5.4 (3.6, 6.1)	0.6
Unknown	2	0	2	

[1] Median (IQR)
[2] Wilcoxon rank sum test

Table 7-18: Proximity to target acetabular cup inclination according to participant group and simulation model for the StR cohort at follow-up.

Proximity to target acetabular cup operative inclination									
Variable	**Overall[1]**	**OI hemipelvis freehand[1]**	**OI hemipelvis MAG[1]**	**OI tilted hemipelvis freehand[1]**	**OI tilted hemipelvis MAG[1]**	**OI hemipelvis with muscle freehand[1]**	**OI hemipelvis with muscle MAG[1]**	**OI tilted hemipelvis with muscle freehand[1]**	**OI tilted hemipelvis with muscle MAG[1]**
Intervention									
Reading									
+/-5	101 (70%)	12 (67%)	14 (78%)	7 (39%)	13 (72%)	13 (72%)	15 (83%)	13 (72%)	14 (78%)
plus 5-10	20 (14%)	2 (11%)	1 (5.6%)	4 (22%)	2 (11%)	3 (17%)	3 (17%)	2 (11%)	3 (17%)
minus 5-10	20 (14%)	3 (17%)	3 (17%)	5 (28%)	3 (17%)	2 (11%)	0 (0%)	3 (17%)	1 (5.6%)
plus 10-15	2 (1.4%)	1 (5.6%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
minus 10-15	1 (0.7%)	0 (0%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Control									
Reading									
+/-5	91 (82%)	9 (64%)	11 (79%)	10 (71%)	12 (86%)	11 (79%)	13 (93%)	12 (92%)	13 (93%)
plus 5-10	9 (8.1%)	1 (7.1%)	2 (14%)	2 (14%)	2 (14%)	1 (7.1%)	0 (0%)	0 (0%)	1 (7.1%)
minus 5-10	8 (7.2%)	3 (21%)	1 (7.1%)	2 (14%)	0 (0%)	1 (7.1%)	1 (7.1%)	0 (0%)	0 (0%)
plus 10-15	3 (2.7%)	1 (7.1%)	0 (0%)	0 (0%)	0 (0%)	1 (7.1%)	0 (0%)	1 (7.7%)	0 (0%)
Unknown	17	2	2	2	2	2	2	3	2

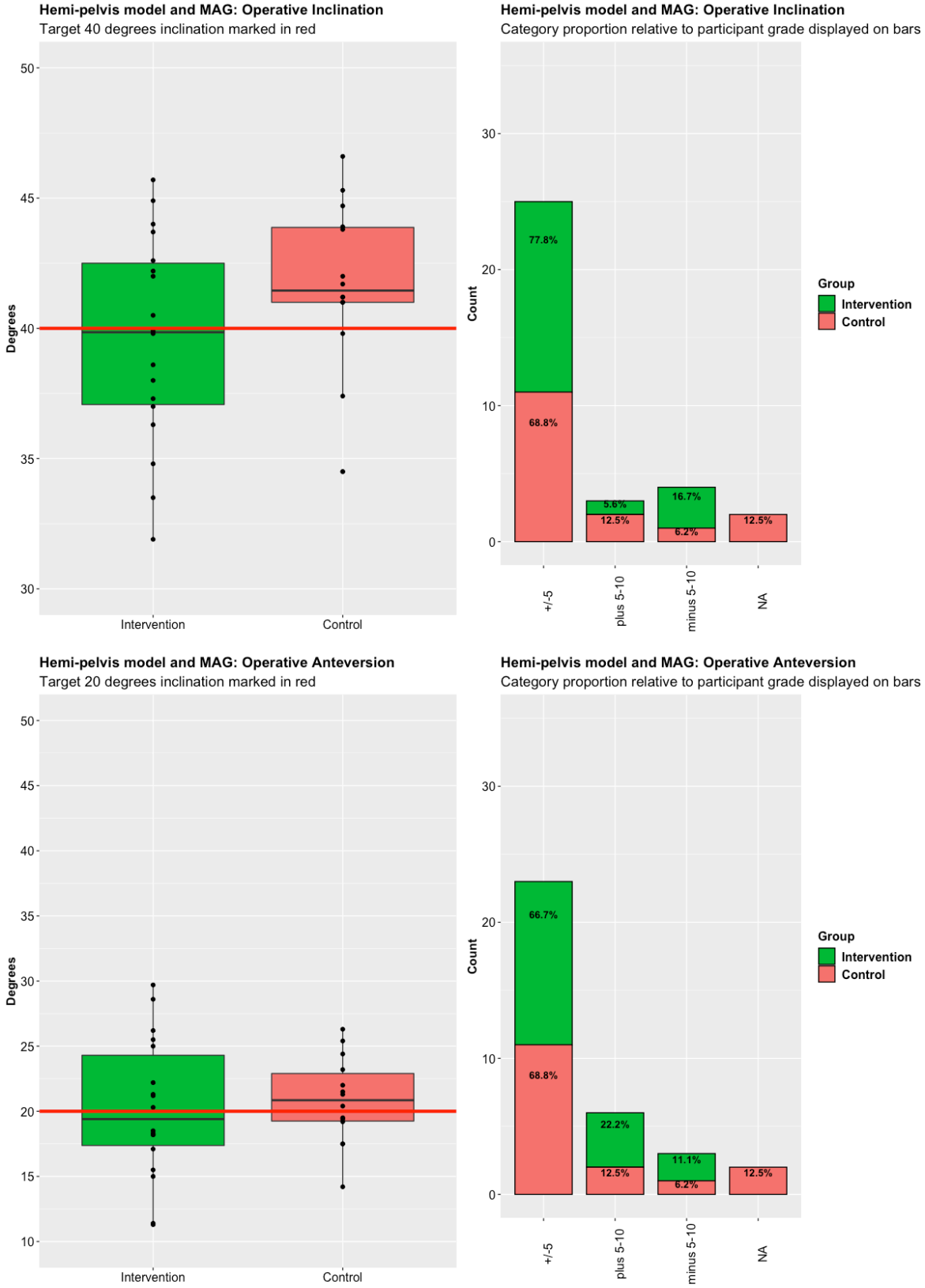
[1] n (%)

Table 7-19: Proximity to target acetabular cup anteversion according to participant group and simulation model for the StR cohort at follow-up.

Proximity to target acetabular cup operative anteversion									
Variable	**Overall[1]**	**OA hemipelvis freehand[1]**	**OA hemipelvis MAG[1]**	**OA tilted hemipelvis freehand[1]**	**OA tilted hemipelvis MAG[1]**	**OA hemipelvis with muscle freehand[1]**	**OA hemipelvis with muscle MAG[1]**	**OA tilted hemipelvis with muscle freehand[1]**	**OA tilted hemipelvis with muscle MAG[1]**
Intervention									
Reading									
+/-5	72 (51%)	7 (39%)	12 (67%)	8 (53%)	10 (56%)	4 (22%)	12 (67%)	9 (50%)	10 (56%)
plus 5-10	30 (21%)	2 (11%)	4 (22%)	2 (13%)	6 (33%)	5 (28%)	4 (22%)	3 (17%)	4 (22%)
minus 5-10	6 (4.3%)	2 (11%)	2 (11%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	1 (5.6%)
plus 10-15	21 (15%)	4 (22%)	0 (0%)	4 (27%)	1 (5.6%)	4 (22%)	0 (0%)	5 (28%)	3 (17%)
plus 15-30	12 (8.5%)	3 (17%)	0 (0%)	1 (6.7%)	0 (0%)	5 (28%)	2 (11%)	1 (5.6%)	0 (0%)
Unknown	3	0	0	3	0	0	0	0	0
Control									
Reading									
+/-5	71 (63%)	5 (36%)	11 (79%)	10 (71%)	13 (93%)	6 (43%)	9 (64%)	8 (57%)	9 (64%)
plus 5-10	30 (27%)	5 (36%)	2 (14%)	3 (21%)	1 (7.1%)	4 (29%)	4 (29%)	6 (43%)	5 (36%)
minus 5-10	2 (1.8%)	1 (7.1%)	1 (7.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 10-15	8 (7.1%)	2 (14%)	0 (0%)	1 (7.1%)	0 (0%)	4 (29%)	1 (7.1%)	0 (0%)	0 (0%)
plus 15-30	1 (0.9%)	1 (7.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Unknown	16	2	2	2	2	2	2	2	2

[1] n (%)

Figure 7-12: Boxplots and barplots showing summary acetabular cup orientation readings using a level hemi-pelvis model and MAG for the StR cohort at follow-up.



7.3.3.4 Change in performance in intervention group

The purpose of this sub-study is to determine the change in performance metrics from baseline to follow-up assessments within the 18 StR participants in the intervention group who had undertaken the additional simulation-based training module in THR.

7.3.3.4.1 Cognitive performance

Multiple choice questionnaire (MCQ)

The overall median average MCQ score in the intervention group at baseline was 11/20 (55%, IQR 3), and a marginal but non-significant increase in score to 12/20 (60%, IQR 6) was observed at follow-up assessment (p=0.2 on Wilcoxon rank sum test). Using a threshold of 14 as the pass mark, overall, 4/18 (22.2%) participants passed at baseline, which increased to 8/18 (44.4%) participants passed at follow-up assessment (p=0.2).

Table 7-20: Summary MCQ results for the StR intervention group at baseline and follow-up assessments.

Multiple choice questionnaire				
Variable	**Overall**, N = 36[1]	**Baseline**, N = 18[1]	**Follow-up**, N = 18[1]	**p-value**[2]
MCQ score	12 (10, 14)	11 (10, 13)	12 (10, 16)	0.2
MCQ outcome				0.2
Pass	12 (33.3%)	4 (22.2%)	8 (44.4%)	
Fail	24 (66.7%)	14 (77.8%)	10 (55.6%)	

[1] Median (IQR); n (%)

[2] Wilcoxon rank sum test; Pearson's Chi-squared test

Component templating

All 18 StR participants in the intervention group completed the baseline and follow-up component templating tasks (table 7-23). No significant differences were observed between assessments regarding the templated cemented stem size (χ^2>0.9), offset (χ^2=0.3), neck length (χ^2=0.7); uncemented acetabular cup size (χ^2=0.5); uncemented stem size (χ^2=0.2), offset (χ^2=0.3), and neck length (χ^2=0.3). Using the consultants templated size range as an indicator of acceptable performance, the percentage of StRs who appropriately templated components improved in three parameters (cemented stem offset, uncemented stem size, and uncemented stem offset); reduced in three parameters (cemented stem size, uncemented acetabular cup size, and uncemented stem neck length); and remained the same in one parameter (cemented stem neck length). The only templating parameter within the StR intervention group noted to significantly improve following simulation training in comparison to consultant performance was the size of the uncemented stem size, which went from 9/18 (50%) at baseline to 15/18 (83%) at follow-up assessment (χ^2=0.034).

7.3.3.4.2 Technical Skills performance

Skin marking

All 18 StR participants in the intervention group completed the baseline skin incision marking task, and 17 (94.4%) completed the follow-up task. For the simulated posterior surgical approach skin marking task the median average and IQR for incision length and curvature was 14cm (IQR 2cm) and 5cm (IQR 2cm) at baseline and 14cm (IQR 4cm) and 5cm (IQR 2cm) at follow-up assessments. No significant differences were observed between baseline and follow-up assessments for the length ($p=1$) or curvature ($p=0.87$) of skin marking for the simulated posterior surgical approach. For the simulated Hardinge surgical approach skin marking task the median average and IQR for incision length and curvature was 13cm (IQR 2cm) and 2.5cm (IQR 1cm) at baseline and 13cm (IQR 1cm) and 3cm (IQR 2cm) at follow-up assessments. No significant differences were observed between baseline and follow-up assessments for the length ($p=0.66$) or curvature ($p=0.06$) of skin marking for the simulated posterior surgical approach.

Component orientation

The femoral stem orientation task was completed by 12/18 (66.7%) of StRs in the intervention group at both baseline and follow-up assessments. The overall median femoral stem version (FSV) was 11.5° (IQR 5.8°), which is 3.5° less than the target of 15° (tables 7-21/22). No significant differences in FSV were found between the baseline and follow-up assessments (p=0.6). At the baseline assessment 7/12 (58.3%) of StRs achieved FSV within 5° of the targets, which increased to 11/12 (91.7%) at follow-up assessments (χ^2=0.3). The acetabular cup orientation tasks were completed by all 18 StRs at both baseline and follow-up assessments. The median average OI and OA across both assessments and all pelvis models used in this study was 40.3° (IQR 38.4°-43.7°) and 24.4° (IQR 21.5°-27.1°), respectively (table 7-21). Although OI decreased, and OA increased in participants from baseline to follow-up assessments no significant differences were found in the median average OI (p=0.11) or OA (p=0.7) between assessments. Only two significant differences were observed between the baseline and follow-up component orientation assessments in this group, namely: a significantly reduced OI when using the level hemi-pelvis model and MAG (median 43.0° at baseline to 39.8° at follow-up; p=0.037), and a significantly increased OA when using the tilted hemi-pelvis model without the MAG (median 20.8° at baseline to 25.2° at follow-up; p=0.008). There were no significant differences observed within this group between the baseline and follow-up assessments in the participants categorical proximity to the target orientation for the femur or acetabular cup orientation tasks.

Table 7-21: Summary component orientation readings from simulated tasks for the StR intervention group at baseline and follow-up assessments.

Component orientation readings				
Variable	**Overall**, N = 36[1]	**Baseline**, N = 18[1]	**Follow-up**, N = 18[1]	**p-value**[2]
Femur model				
Femoral stem version	11.5 (9.2, 15.0)	11.2 (4.5, 15.1)	11.5 (10.0, 14.2)	0.6
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	40.6 (37.0, 44.2)	42.5 (38.9, 46.8)	39.0 (36.8, 43.4)	0.2
OA	27.0 (18.5, 32.4)	28.1 (25.5, 32.2)	25.4 (18.4, 32.8)	0.8
Hemi-pelvis model and MAG				
OI	41.9 (38.5, 43.8)	43.0 (41.0, 44.2)	39.8 (37.1, 42.5)	**0.037**
OA	21.2 (18.2, 25.1)	22.5 (20.4, 24.9)	19.4 (17.4, 24.3)	0.2
Tilted hemi-pelvis model freehand				
OI	39.9 (36.9, 44.7)	39.9 (37.9, 44.2)	39.9 (33.6, 44.1)	0.5
OA	24.8 (19.3, 29.0)	25.6 (19.4, 28.6)	23.4 (19.6, 29.8)	0.6
Tilted hemi-pelvis model and MAG				
OI	39.5 (37.9, 42.8)	41.2 (38.1, 43.8)	39.2 (37.8, 42.4)	0.4
OA	20.9 (17.1, 25.5)	20.4 (16.5, 24.4)	21.5 (18.7, 26.2)	0.6
Hemi-pelvis with muscle model freehand				
OI	42.0 (37.9, 46.2)	44.7 (38.8, 48.6)	40.8 (37.5, 42.7)	0.079
OA	29.9 (24.1, 36.0)	29.1 (23.4, 35.9)	29.9 (25.2, 35.4)	0.9
Hemi-pelvis with muscle model and MAG				
OI	41.8 (39.0, 43.9)	42.5 (40.0, 44.3)	41.7 (38.8, 43.3)	0.5
OA	23.1 (20.6, 26.0)	21.6 (20.1, 25.4)	23.8 (22.2, 25.9)	0.2
Tilted hemi-pelvis with muscle model freehand				
OI	40.5 (38.4, 44.2)	42.8 (39.0, 46.0)	40.0 (38.0, 43.5)	0.3
OA	23.3 (20.4, 28.5)	20.8 (18.4, 24.1)	25.2 (23.3, 31.7)	**0.008**
Tilted hemi-pelvis with muscle model and MAG				
OI	39.2 (37.1, 43.7)	39.2 (36.7, 41.5)	39.8 (37.6, 44.4)	0.5
OA	21.8 (19.4, 26.6)	21.2 (18.6, 24.2)	22.8 (20.5, 27.1)	0.2
Summary figures for all acetabular cup orientation models				
OI	40.3 (38.4, 43.7)	41.4 (39.3, 44.3)	39.1 (38.0, 42.7)	0.11
OA	24.4 (21.5, 27.1)	24.4 (21.7, 26.6)	24.6 (21.6, 27.1)	0.7

[1] Median (IQR)

[2] Kruskal-Wallis rank sum test

Table 7-22: Summary component orientation variation from target during simulated tasks for the StR intervention group at baseline and follow-up assessments.

Component orientation variation from target				
Variable	**Overall**, N = 36[1]	**Baseline**, N = 18[1]	**Follow-up**, N = 18[1]	**p-value**[2]
Femur model				
Femoral stem version	-3.5 (-5.8, 0.0)	-3.8 (-10.5, 0.1)	-3.5 (-5.0, -0.8)	0.6
Unknown	12	6	6	
Hemi-pelvis model freehand				
OI	0.6 (-3.1, 4.2)	2.4 (-1.1, 6.8)	-0.9 (-3.2, 3.4)	0.2
OA	7.0 (-1.5, 12.4)	8.1 (5.5, 12.2)	5.4 (-1.6, 12.8)	0.8
Hemi-pelvis model and MAG				
OI	1.9 (-1.5, 3.8)	3.0 (1.0, 4.2)	-0.2 (-2.9, 2.5)	**0.037**
OA	1.2 (-1.8, 5.1)	2.5 (0.4, 4.9)	-0.6 (-2.6, 4.3)	0.2
Tilted hemi-pelvis model freehand				
OI	-0.1 (-3.1, 4.7)	-0.1 (-2.1, 4.2)	-0.1 (-6.4, 4.1)	0.5
OA	4.8 (-0.7, 9.0)	5.6 (-0.6, 8.6)	3.3 (-0.4, 9.8)	0.6
Tilted hemi-pelvis model and MAG				
OI	-0.5 (-2.1, 2.8)	1.2 (-1.9, 3.8)	-0.8 (-2.2, 2.4)	0.4
OA	0.8 (-2.9, 5.5)	0.4 (-3.5, 4.5)	1.5 (-1.3, 6.2)	0.6
Hemi-pelvis with muscle model freehand				
OI	2.1 (-2.1, 6.2)	4.7 (-1.2, 8.6)	0.8 (-2.5, 2.7)	0.079
OA	9.8 (4.1, 16.0)	9.2 (3.4, 15.9)	9.8 (5.2, 15.3)	0.9
Hemi-pelvis with muscle model and MAG				
OI	1.8 (-1.1, 3.9)	2.4 (0.1, 4.3)	1.7 (-1.2, 3.3)	0.5
OA	3.1 (0.6, 6.0)	1.6 (0.1, 5.4)	3.8 (2.2, 5.9)	0.2
Tilted hemi-pelvis with muscle model freehand				
OI	0.4 (-1.6, 4.2)	2.8 (-1.0, 6.0)	-0.1 (-2.0, 3.5)	0.3
OA	3.3 (0.4, 8.5)	0.8 (-1.6, 4.1)	5.2 (3.3, 11.7)	**0.008**
Tilted hemi-pelvis with muscle model and MAG				
OI	-0.8 (-2.9, 3.7)	-0.8 (-3.3, 1.5)	-0.2 (-2.4, 4.4)	0.5
OA	1.8 (-0.6, 6.6)	1.2 (-1.4, 4.2)	2.8 (0.5, 7.1)	0.2
Summary figures for all acetabular cup orientation models				
OI	0.3 (-1.6, 3.7)	1.4 (-0.7, 4.3)	-0.9 (-2.0, 2.7)	0.11
OA	5.2 (1.9, 8.2)	5.0 (2.1, 8.4)	5.3 (2.3, 7.8)	0.7

[1] Median (IQR)

[2] Wilcoxon rank sum test

Table 7-23: Proximity to target acetabular cup inclination according to participant group and simulation model for the StR intervention group at baseline and follow-up assessments.

Proximity to target acetabular cup operative inclination									
Variable	**Overall[1]**	**OI hemipelvis freehand[1]**	**OI hemipelvis MAG[1]**	**OI tilted hemipelvis freehand[1]**	**OI tilted hemipelvis MAG[1]**	**OI hemipelvis with muscle freehand[1]**	**OI hemipelvis with muscle MAG[1]**	**OI tilted hemipelvis with muscle freehand[1]**	**OI tilted hemipelvis with muscle MAG[1]**
Baseline									
Reading									
+/-5	102 (71%)	10 (56%)	16 (89%)	13 (72%)	12 (67%)	8 (44%)	16 (89%)	12 (67%)	15 (83%)
plus 5-10	19 (13%)	2 (11%)	2 (11%)	1 (5.6%)	2 (11%)	5 (28%)	1 (5.6%)	4 (22%)	2 (11%)
minus 5-10	7 (4.9%)	1 (5.6%)	0 (0%)	2 (11%)	1 (5.6%)	1 (5.6%)	1 (5.6%)	0 (0%)	1 (5.6%)
plus 10-15	11 (7.6%)	3 (17%)	0 (0%)	2 (11%)	2 (11%)	2 (11%)	0 (0%)	2 (11%)	0 (0%)
minus 10-15	2 (1.4%)	1 (5.6%)	0 (0%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
plus 15-30	3 (2.1%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	2 (11%)	0 (0%)	0 (0%)	0 (0%)
Follow up									
Reading									
+/-5	101 (70%)	12 (67%)	14 (78%)	7 (39%)	13 (72%)	13 (72%)	15 (83%)	13 (72%)	14 (78%)
plus 5-10	20 (14%)	2 (11%)	1 (5.6%)	4 (22%)	2 (11%)	3 (17%)	3 (17%)	2 (11%)	3 (17%)
minus 5-10	20 (14%)	3 (17%)	3 (17%)	5 (28%)	3 (17%)	2 (11%)	0 (0%)	3 (17%)	1 (5.6%)
plus 10-15	2 (1.4%)	1 (5.6%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
minus 10-15	1 (0.7%)	0 (0%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

[1] n (%)

Table 7-24: Proximity to target acetabular cup anteversion according to participant group and simulation model for the StR intervention group at baseline and follow-up assessments.

Proximity to target acetabular cup operative anteversion									
Variable	**Overall[1]**	**OA hemipelvis freehand[1]**	**OA hemipelvis MAG[1]**	**OA tilted hemipelvis freehand[1]**	**OA tilted hemipelvis MAG[1]**	**OA hemipelvis with muscle freehand[1]**	**OA hemipelvis with muscle MAG[1]**	**OA tilted hemipelvis with muscle freehand[1]**	**OA tilted hemipelvis with muscle MAG[1]**
Baseline									
Reading									
+/-5	80 (56%)	3 (17%)	11 (61%)	8 (44%)	12 (67%)	6 (33%)	13 (72%)	14 (78%)	13 (72%)
plus 5-10	28 (19%)	7 (39%)	4 (22%)	6 (33%)	2 (11%)	3 (17%)	3 (17%)	1 (5.6%)	2 (11%)
minus 5-10	8 (5.6%)	1 (5.6%)	2 (11%)	0 (0%)	2 (11%)	0 (0%)	0 (0%)	1 (5.6%)	2 (11%)
plus 10-15	16 (11%)	4 (22%)	1 (5.6%)	3 (17%)	2 (11%)	4 (22%)	1 (5.6%)	1 (5.6%)	0 (0%)
plus 15-30	12 (8.3%)	3 (17%)	0 (0%)	1 (5.6%)	0 (0%)	5 (28%)	1 (5.6%)	1 (5.6%)	1 (5.6%)
Follow up									
Reading									
+/-5	72 (51%)	7 (39%)	12 (67%)	8 (53%)	10 (56%)	4 (22%)	12 (67%)	9 (50%)	10 (56%)
plus 5-10	30 (21%)	2 (11%)	4 (22%)	2 (13%)	6 (33%)	5 (28%)	4 (22%)	3 (17%)	4 (22%)
minus 5-10	6 (4.3%)	2 (11%)	2 (11%)	0 (0%)	1 (5.6%)	0 (0%)	0 (0%)	0 (0%)	1 (5.6%)
plus 10-15	21 (15%)	4 (22%)	0 (0%)	4 (27%)	1 (5.6%)	4 (22%)	0 (0%)	5 (28%)	3 (17%)
plus 15-30	12 (8.5%)	3 (17%)	0 (0%)	1 (6.7%)	0 (0%)	5 (28%)	2 (11%)	1 (5.6%)	0 (0%)
Unknown	3	0	0	3	0	0	0	0	0

[1] n (%)

Figure 7-13: Boxplots and barplots showing summary acetabular cup orientation readings using a level hemi-pelvis model and MAG for the StR cohort at baseline and follow-up assessments.

Target orientation marked with solid red line.

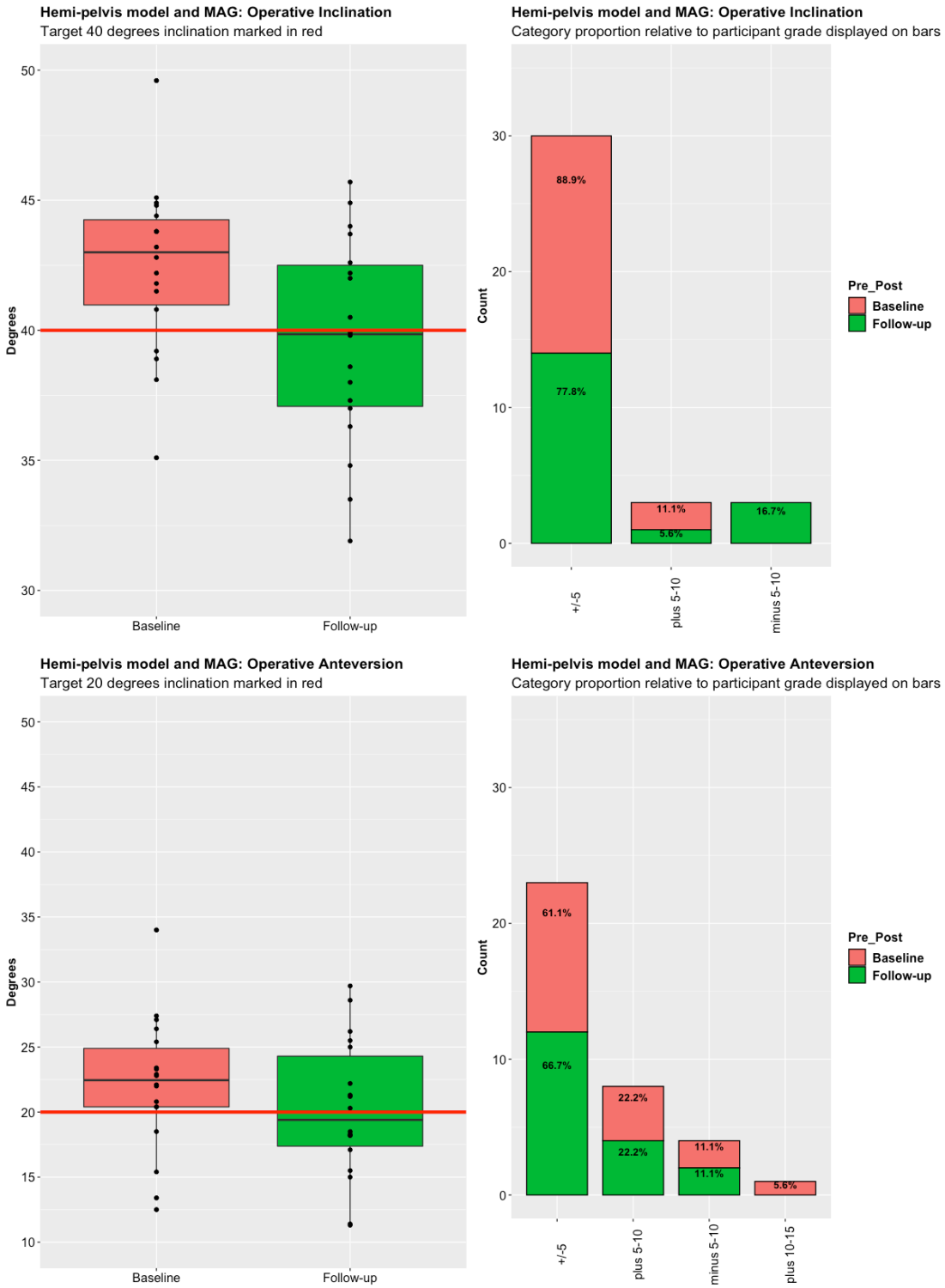
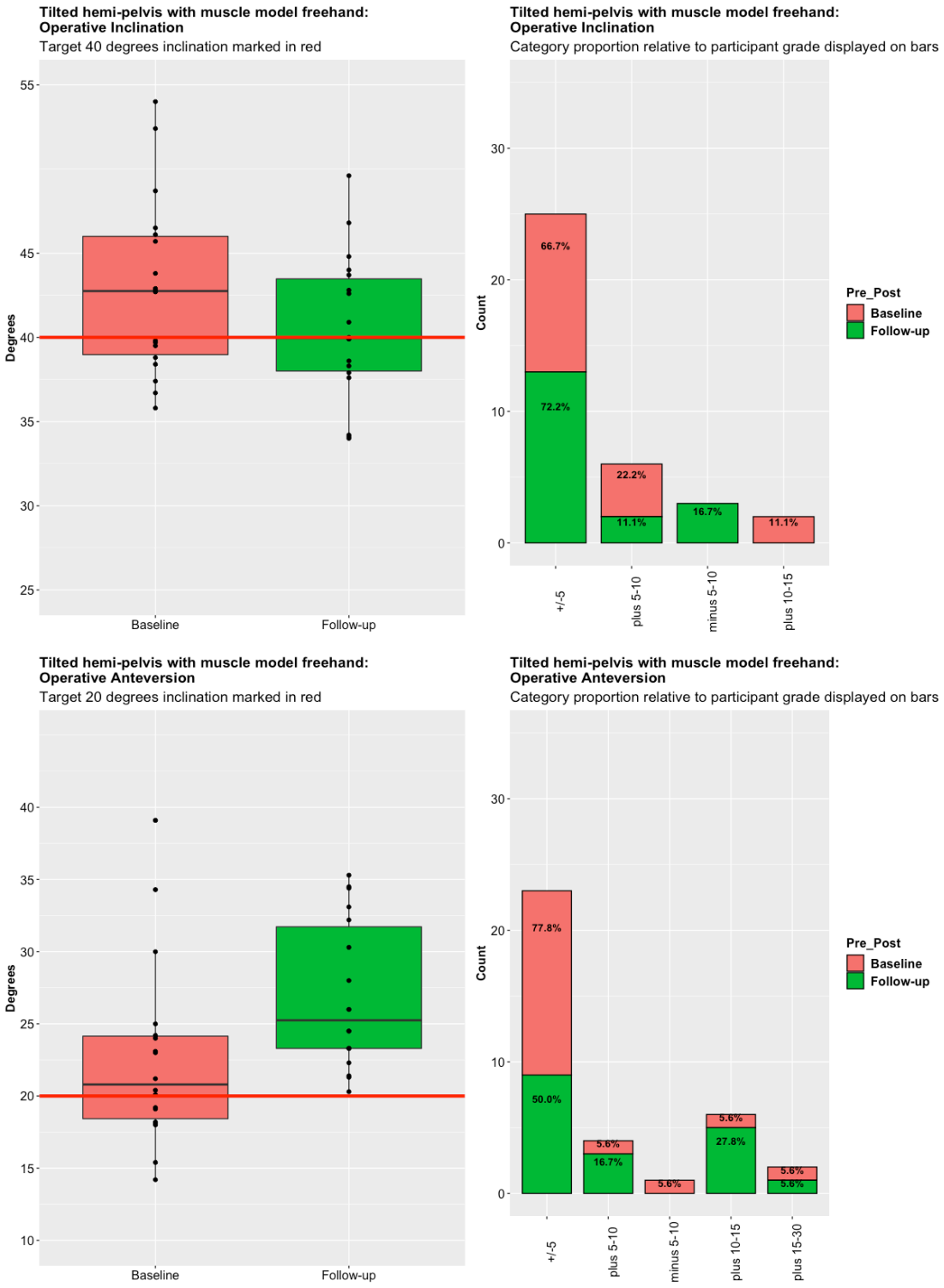


Figure 7-14: Boxplots and barplots showing summary acetabular cup orientation readings using a tilted hemi-pelvis model with simulated soft tissues without the MAG for the StR cohort at baseline and follow-up assessments.

Target orientation marked with solid red line.



7.3.3.5 Participant feedback following completion of primary THR training module

Written and verbal feedback was invited from all participants who attended the simulation-based learning module in primary THR (the 'intervention' StR subgroup). The written feedback was collected using an electronic questionnaire which was constructed using a template on the online platform google forms (Google Forms; Google LLC, Mountain View CA). This short unvalidated questionnaire contained 11 categorical questions and 3 free-text questions. The categorical questions were rated using a 5-point Likert scale, with the options: strongly disagree, disagree, unsure, agree, or strongly agree. Overall, 15/18 (83%) of StR participants from the intervention group voluntarily completed the feedback form following completion of the simulation-based training module in THR. The categorical responses are summarised in table 7-25.

Table 7-25: Summary of participant responses to categorical questions in post-training feedback questionnaire.

Post THR simulation module participant feedback	
Question	**N = 15[1]**
Q1. The session was well organised	
Strongly Agree	12 (80%)
Agree	3 (20%)
Q2. Teaching & presentations met the learning objectives	
Strongly Agree	13 (87%)
Agree	2 (13%)
Q3. Content was pitched at the right level	
Strongly Agree	13 (87%)
Agree	2 (13%)
Q4. The teaching session was completed within the allocated time	
Agree	5 (33%)
Strongly Agree	9 (60%)
Unsure	1 (6.7%)
Q5. The teaching session was interactive	
Strongly Agree	13 (87%)
Agree	2 (13%)
Q6. The location and facilities were convenient	
Strongly Agree	13 (87%)
Agree	2 (13%)
Q7. The simulation models used were RELEVANT to the objectives	
Strongly Agree	13 (87%)
Agree	2 (13%)
Q8. The simulation models used REPLICATED the task	
Agree	5 (33%)
Strongly Agree	10 (67%)
Q9. The simulation models used were EASY TO USE	
Strongly Agree	12 (80%)
Agree	3 (20%)
Q10. The delegate workbook was a useful addition to the course	
Strongly Agree	15 (100%)
Q11. Overall I would rate the session as	
Very Good	15 (100%)
[1] n (%)	

A selection of the free-text responses to the following three questions are written below:

Question 1: What did you learn from the training session?

- *A lot of useful practical tips to apply the basic knowledge, and supplement what I had observed in theatre*
- *Principles of THR, practical tips and tricks, hands on experience*
- *The objectives of THR, particularly implant positioning*
- *Review of primary hip techniques and theory*
- *A good overview of the basic principles & some new techniques*
- *Good overall understanding about the principles and important aspects of hip arthroplasty*
- *Fundamentals of THR...finally!*
- *Covered essentially all the key foundations for THR. Best addition would be ability to repeatedly practice the stem/cup implantation etc.*
- *I learned a lot - I have not done hip arthroplasty as a job yet so this was an excellent overview as to what I can expect to learn when I move to my next job*
- *Learnt excellent tips and tricks about the THR e.g., OI should aim at nearly 9° less than the RI due to the pelvic tilt to achieve the right acetabular inclination. Another thing is how to measure the FO and AO. Overall, it is one of the best teaching courses I have attended.*
- *To assess angles and very useful handouts*
- *How to template for a THR. Gained more experience in correct angulation for acetabular reaming.*
- *Factors affecting THR outcomes and how to improve on these. Templating. Excellent session.*
- *Greater understand of pelvic tilt and how this can impact cup positioning. An evaluation of the accuracy of my stems and cup positioning*

Question 2: What changes could be made to the training session to improve it?

- *Roll out this type of educational course to other indicative operations*
- *Faculty to allow concurrent assessments (difficult due to covid restrictions)*
- *Slightly rushed perhaps, but probably because we were trying to finish before paeds teaching...*
- *To potentially consider cadaveric models for simulation*
- *Could include more exercises (based around theory) during the lectures*
- *As above*
- *Just expand it to more sessions for the other arthroplasty joints!! Knees, shoulders, etc. This was a brilliant session for the hips.*
- *Refreshments*
- *I would recommend making the course very clear and consistent about which type of THR is going to be used and taught on e.g., Stryker or Corin.*
- *Allocate more FRCS exam topics*
- *Allocate more time so things are less rushed.*

Question 3: Any other comments or constructive feedback:

- *The workbook is excellent - exactly the sort of resource that would be useful for all registrars in training. If possible, it would be great to have that available to all registrars on the rotation going forwards.*
- *Having attended over 30 large national and international professional courses, I can confidently say this was the best course I have been on. It was exceptionally well organised and very effective. I feel much more confident starting my arthroplasty placement.*
- *Overall Excellent opportunity for me to learn about the basics and principles of hip arthroplasty. This will now allow me to gain some insight into the aspects of the subject that I need to learn and read up on. The booklet is excellent, and the content is brilliant. A lot of thought and hardworking has clearly gone into planning the course. Thank you very much.*
- *Excellent day and course. Thank you.*
- *As above - this was brilliant - it should be a pre-requisite for junior registrars to do this prior to commencing a hip arthroplasty firm; it would also be good to expand this type of training to include knee arthroplasty etc*
- *I would like to thank Dan very much for being so helpful, informative, and engaging teacher. I will be grateful if you could arrange a TKR course in the future.*
- *A fantastic learning opportunity that allows you to practice and ask questions in a supportive environment. More sessions like this are needed.*
- *This was a fantastic session, and I would highly recommend to all Registrars.*

7.3.4 Discussion

7.3.4.1 Summary and relevance of findings

This randomised controlled study investigating the impact of a simulation training module on the cognitive and technical skills performance of surgical trainees (StRs) in simulated aspects of total hip replacement has identified several novel findings. The combination of strong recruitment (n=34) and retainment of StR participants between the baseline and follow-up assessments in this study (32/34 or 94%) provide adequate statistical power to draw conclusions based on the results.

The use of MCQs to assess orthopaedic trainees cognitive performance in relation to THR has been reported in a recent simulation-based study. (79) In this study, no significant differences were observed between the StR intervention and control groups in MCQ scores or pass rates at either baseline or follow-up assessments. A non-statistically significant greater percentage of participants from the intervention group achieved a passing score in the follow-up assessment in comparison to control group participants (44.4% versus 31.2%). The percentage of participants from the intervention group who passed the MCQ doubled from 22.2% (4/18) at baseline to 44.4% (8/18) at follow-up assessment, which suggests a trend for improved knowledge following simulation training. As mentioned previously, the passing score for both pre- and post-course MCQs, may have been set too high to determine the 'minimally competent trainee', and further validation and possible adjustments to the passing score of these MCQ tests should be considered.

No significant differences were observed between the StR intervention and control groups in their baseline or follow-up component templating assessments, including in comparison to the consultant acceptable reference range of templated components. The only exception to this finding was in relation to the acceptable modular neck length selected by StRs in comparison to consultants, with 18/18 (100%) of participants in the intervention group selecting an acceptable neck length in comparison to 12/16 (75%) in the control group. However, the clinical relevance of this finding is likely insignificant. Within the StR intervention group, no significant differences were observed

between baseline and follow-up assessments regarding the templated parameters for the cemented stem, uncemented cup or uncemented stem. The percentage of StRs who appropriately templated components in comparison to consultants improved in three parameters (cemented stem offset, uncemented stem size, and uncemented stem offset); reduced in three parameters (cemented stem size, uncemented acetabular cup size, and uncemented stem neck length); and remained the same in one parameter (cemented stem neck length). However, the only templating parameter within the StR intervention group which significantly improved following simulation training in comparison to consultant performance was the size of the uncemented stem size, which went from 9/18 (50%) at baseline to 15/18 (83%) at follow-up assessment (χ^2= 0.034). This observation may reflect an increase in confidence of StRs to appropriately size uncemented femoral stems following simulation training. Studies have reported an association between increased surgeon experience and adequate preoperative templating of femoral components, but not acetabular components. (315, 316) This finding may have important clinical implications, as undersized uncemented femoral stems have been associated with poorer radiological appearances and increased early revision rates. (317, 318)

No significant differences were observed between the StR intervention and control groups in relation to the length or curvature of the skin markings for either the posterior or Hardinge approaches to the hip at their baseline or follow-up assessments. Furthermore, within the StR intervention group no significant changes were observed in the length or curvature of the skin markings for either the posterior or Hardinge approaches to the hip between baseline and follow-up assessments. This observation suggests that simulation training did not alter the participants perception on the length or curvature of incision used for THR. However, this simulated task did not demonstrate high fidelity, as participants did not have to perform the full surgical approach in the simulated model following marking the skin incision. Intra-operatively surgical trainees and their trainers may require extensions to be made to skin incisions when performing THR to allow adequate exposure to perform this operation under direct supervision. Therefore, the findings of this task may not accurately reflect clinical practice.

Regards the component orientation assessments no significant differences were found in the median average acetabular cup OI or OA between StR participant groups at baseline or follow-up assessments. At baseline, the median average OI and OA across both StR groups and all pelvis models was 41.4° (IQR 39.6°-44.3°) and 24.3° (IQR 21.9°-26.7°), in comparison to 39.9° (IQR 38.4°-42.3°) and 24.2° (IQR 22.5°-26.1°) at follow-up assessments, respectively. StRs within the intervention group demonstrated median average OI and OA across both assessments and all pelvis models of 40.3° (IQR 38.4°-43.7°) and 24.4° (IQR 21.5°-27.1°). Within the StR intervention group, non-significant reductions in median OI readings and increased median OA readings were observed between the overall baseline and follow-up assessments. Two significant differences were observed within the StRs intervention group between the baseline and follow-up acetabular cup component orientation assessments, namely: a significant reduction in OI when using the level hemi-pelvis model and MAG (median 43.0° at baseline versus 39.8° at follow-up; p=0.037), and a significant increase in OA when using the tilted hemi-pelvis model without the MAG (median 20.8° at baseline versus 25.2° at follow-up; p=0.008). The trend of reducing OI and increasing OA was seen in both the fellow and consultant groups in comparison to the StRs within study A and may indicate an overall non-significant improvement in cup orientation following simulation training. However, no significant differences were observed in the StR intervention group from baseline to follow-up assessments in their categorical proximity to the target orientation in acetabular cup orientation tasks.

At the follow-up assessment, the only significant difference in acetabular cup orientation readings between StRs in the intervention and control groups was observed when using the level pelvis model and MAG. In this task, the control group StRs demonstrated significantly higher OI readings than the intervention group when performing this task (median 43.1° versus 39.2°, p=0.046). At the follow-up assessment there were also no significant differences observed between the intervention and control groups in their categorical proximity to the target orientation in acetabular cup orientation tasks.

The overall median error in acetabular cup orientation readings (OI and OA) achieved by StRs in this study are comparably less than what has been reported in other simulation-based studies and are more consistent with the performances observed in trainees following additional simulation training. (66, 78, 92, 236) At the baseline assessment in this study, the overall median error in OI and OA across all StRs was 1.4° and 5.3°, respectively, and at the follow-up assessments, this was -0.1° and 5.4°, respectively. As previously mentioned, no significant difference was observed between StRs in the intervention or control groups at either baseline or follow-up assessments. Grammatopolous *et al* reported that a mixed group of 21 surgeons and trainees (9 trainers and 12 trainees) OI was underestimated by mean value of 4° and OA was overestimated by mean value of 11°. (236) Using the same target acetabular cup orientations of 40° OI and 20° OA as set in this study, Logishetty *et al* reported a mean OI error of 3° and OA error of 4° in a group of VR-trained orthopaedic trainees, and a mean OI error of 15° and OA error of 16° in a control group of orthopaedic trainees. (78) A subsequent study of visuospatial performance in VR-simulated anterior approach THR by Logishetty *et al* reported a baseline mean OI error of 14° and OA error of 16° in a group of 32 orthopaedic trainees, in comparison to a mean OI error of 5° and OA error of 4° in a control group of 4 expert orthopaedic surgeons. Following delivery of a competency-based simulation training curriculum the mean OI and OA errors within the orthopaedic trainee group reduced to 4° and 6°, respectively, which is more in keeping with the results of this study. (66)

No significant differences were found between the StR intervention and control groups in their baseline or follow-up femoral stem component orientation tasks. The overall median FSV observed across all StRs at baseline was 10.7°, and 12.5° at follow-up assessments. Given the target of 15° anteversion, StRs underestimated FSV by a median value of 4.3° at baseline and 2.5° at follow-up assessments, respectively. StRs within the intervention group demonstrated a non-significant overall improvement in accuracy of FSV between baseline (11.2°, IQR 4.5-15.1°) and follow-up (11.5°, IQR 10-14.2°) assessments (p=0.6). At the baseline assessment, 64% (14/22) of all StRs achieved FSV within 5° of the target, which increased to 82% (18/22) at the follow-up assessment. This observation of improved FSV readings was more pronounced in StR intervention group, where

58.3% (7/12) of participants achieved FSV within 5° of the target at baseline assessment, which increased to 91.7% (11/12) at the follow-up assessment. No published scientific article has investigated or reported on the ability of orthopaedic surgeons or surgical trainees to achieve a desired femoral stem version in a simulated setting, so this is a novel finding of this research.

The responses from the trainee questionnaire, which was issued to all recruited participants, has also revealed some interesting findings. Only 38% of respondents (13/34) believe the trauma & orthopaedic surgery training program will meet their requirements for future clinical practice. Furthermore, despite most participants expressing an interest in pursuing a future career in adult arthroplasty (18/34 or 52.9%), only 50% of trainees (17/34) have attended a recognised training course related to this sub-specialty. Most participants (19/34 or 55.9%) believed that a training course in THR should be undertaken during the first year of specialty training (PGY1/ST3). The results from the post-simulation training module feedback questionnaire, which was completed by 83% of attendees (15/18) highlight both the demand for and educational benefits of this training module. All respondents rated the simulation training module as very good, and strongly agreed that the delegate workbook was a useful addition to the practical face to face sessions. This feedback alone validates the usefulness and importance of this simulation training module despite the modest and non-significant improvements in cognitive and technical skills performance exhibited by the surgical trainees who attended the module in comparison to control participants.

7.3.4.2 Limitations of study

This study focused on investigating the differences in performance metrics between surgeons at a group level. The groups in this study were determined based upon medical experience level (study A), or randomisation of participants within the same grade into an intervention and control groups (study B). This methodology may obfuscate further findings, such as the individual benefits that some participants gain from focussed additional training, or the impact of training year (ST3-ST8; PGY1-6) on performance metrics with and without additional simulation training. Future analysis of this data or further studies may choose to focus on the individual rather than group changes in

performance metrics in StR participants who received additional simulation training. This analysis methodology may reveal that some participants improve more markedly than others, but that the effect of these changes are diminished at the group level. Analysis of the change in performance metrics from baseline to follow-up in the control group participants may also enhance the overall understanding of the impact of simulation-based training in THR.

7.4Conclusions

The findings of these linked laboratory-based research studies have identified several novel findings. Regards the MCQ, although a non-significantly higher proportion of fellows achieved a pass in comparison to StRs (44.4% versus 20.6%, respectively), neither the absolute score or pass rate of the MCQ were able to differentiate between fellow and StR groups. The results of study B demonstrated that a greater but statistically non-significant percentage of participants from the StR intervention group achieved a passing score in the follow-up assessment in comparison to control group participants (44.4% versus 31.2%, respectively). Furthermore, the percentage of StR participants from the intervention group passing the MCQ doubled from 22.2% at baseline to 44.4% at follow-up assessment, suggesting a trend for improved knowledge acquisition in THR following simulation training.

Regards the component templating task, the results of study A demonstrated no significant differences between consultants, fellows, or StRs. This finding suggests that component templating alone is not reliable in differentiating surgeons based upon their level of experience. Furthermore, no significant differences were observed from baseline to follow-up assessments between the StR intervention and control groups, or within the StR intervention group in study B. However, the size of uncemented femoral stems templated by StRs from the intervention group significantly improved following simulation training in comparison to sizes templated by consultants (50% at baseline to 83.3% at follow-up assessment, χ^2=0.034).

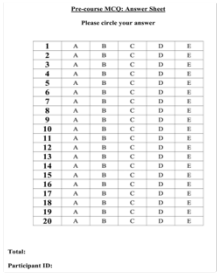
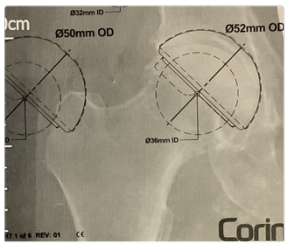
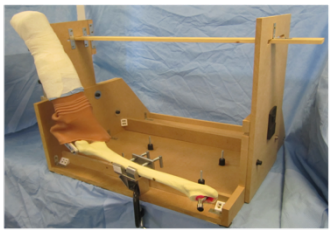
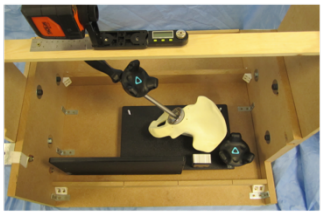
Regards the skin incision marking task, the results of study A demonstrated that consultants marked a significantly shorter length of skin incision than StRs, but not fellows for the posterior approach to the hip joint (median 10cm versus 14cm, respectively, p=0.04). There were no significant differences between groups in the curvature of the posterior or Hardinge approach, or in the length of the Hardinge approach. Furthermore, no significant differences were observed from baseline to follow-up assessments between the StR intervention and control groups, or within the StR intervention group in relation to the length or curvature of the skin markings for either the posterior or Hardinge approaches to the hip joint.

Regards the component orientation tasks, the findings of the femoral stem orientation task are novel as no published study has reported the ability of surgeons to achieve accurate femoral stem version. The results of study A demonstrated an overall median femoral stem anteversion (FSV) across participant groups of 11.0° (IQR 8.5°), with no significant differences in FSV between groups. The overall median FSV was therefore 4° less than the target of 15°. The results of study B demonstrate an overall median FSV across all StRs of 10.7° and 12.5° at baseline and follow-up assessments, respectively. These readings are within 5° of the target 15.0°, which suggests that StRs are accurate in achieving a target FSV in a simulated model. However, no significant differences were found between baseline and follow-up FSV readings in the StR group. Although the ability of surgeons to insert an acetabular cup in a specified orientation during simulated THR has previously been investigated and reported, the results of study A demonstrate a high degree of accuracy in acetabular cup orientation across surgeons with different levels of experience. The median average OI and OA across all participant groups and pelvis models used were 40.9° and 24.8°, respectively. Consultants overestimated OA by a median average of 13.5° and underestimated OI by a median average of 1.6° across all pelvic models in this study. Overall, both fellows and StRs overestimated OA by a median average of 10.8° and 5.3°, respectively. However, fellows underestimated OI by a median average of 0.3°, and StRs overestimated OI by a median average of 1.4°. Although no significant differences were found in the median average OI between participant groups (p=0.15), significant differences were found in the median average OA between participant groups (p= 0.035). This difference was

due to significantly higher OA in the fellow group in comparison to the StR group. There were no significant differences in the median average OI or OA between consultants and any other group. It is interesting to note that using a MAG reduced the average OA readings by consultants, fellows, and StRs in all models during this study, which may reflect a subconscious desire of surgeons to increase anteversion in the absence of visual or mechanical cues. The results of study B demonstrate that the overall median error in acetabular cup OI and OA achieved by StRs are comparably less than what has been reported in other simulation-based studies and are consistent with a higher level of technical skills performance observed in more experienced surgeons. However, no significant differences were found in the median average acetabular cup OI or OA or categorical proximity to the target acetabular cup orientation between StR participant groups at baseline or follow-up assessments. Within the StR intervention group, non-significant reductions in median OI and increased median OA readings were observed between baseline and follow-up assessments. This finding suggests non-significant improvements (closer to those observed in fellows and consultants) in achieving a desired acetabular cup orientation following simulation training.

In summary, the findings outlined within these linked studies have identified several differences in the cognitive and technical skills performances of surgeons in simulated aspects of THR based upon their level of experience. The next step is to assess the transferability of technical skills and knowledge acquired from a simulated environment in StRs into the real-world environment of an operating theatre when performing primary elective THR. The next chapter explores this key step investigating the impact of additional simulation training on the intra-operative performance metrics of StRs and both patient and institutional outcome parameters following this operation.

Figure 7-15: Summary findings of studies A and B.

	Study A	Study B
1. Multiple Choice Questionnaire 	Increased pass rate in fellows compared to StRs (44.4% vs. 20.6%) MCQ unable to reliably differentiate between fellows and StRs	Greater but non-significant increase in pass rate in intervention vs. control group (44.3% vs. 20.6%) Pass rate doubled from baseline to f/u assessments following simulation training
2. Component Templating Task 	No significant differences between consultants, fellows, and StRs	No significant differences from baseline to f/u assessments between StR groups Femoral stem size improved in comparison to consultants in intervention group following simulation training
3. Skin Marking Task 	Significantly shorter length skin incision in consultants than StRs, but not fellows in posterior approach No differences between groups in the curvature of the posterior or Hardinge approach, or the length of the Hardinge approach	No significant differences from baseline to f/u assessments in length or curvature of skin incisions marked for the posterior or Hardinge approaches between StR groups
4. Femoral Stem Orientation Task 	Target FSV 15° Median FSV 11.0° across all participant groups No statistically significant differences in FSV between groups	Target FSV 15° Median FSV across all StRs 10.7° and 12.5° at baseline and f/u assessments, respectively No statistically significant differences in FSV between groups
5. Acetabular Cup Orientation Task 	Target OI 40°/OA 20° Median OI/OA across all participant groups and models used 40.9°/24.8°, respectively No statistically significant differences in OI between groups, but increased OA in fellows compared to StRs	No statistically significant differences in median OI/OA or proximity to target between StR groups at baseline or f/u assessments Median OI/OA across both StR groups 41.4°/24.3° at baseline and 39.9°/24.2° at f/u assessments, respectively

8. Intra-operative surgeon performance and patient outcomes in primary elective total hip replacement.

8.1 Introduction

These linked studies aim to investigate the technical skills performance metrics of surgeons during primary elective THR, and both patient and institutional outcome metrics following this operation. Motion analysis techniques are combined with findings from previous study chapters and other validated objective outcome measures to provide a detailed insight into surgeon performance and patient outcomes for this operation. The purpose of study A is to determine if any significant differences exist in these outcome metrics in relation to surgeon grade (consultant/fellow/specialty registrar). Subsequently, study B aims to determine the impact of additional simulation training on these outcome metrics in operations performed by supervised specialty registrars (StRs). Within study B, the cohort of StR participants were randomised to receive standardised training (control group), or additional simulation-based training (intervention group) as outlined in chapter 5. The surgeon-specific, patient-specific, and institutional outcome metrics used are uniform throughout both studies. Surgeon-specific technical skills performance metrics include the time taken to perform the overall operation, and for each defined step as outlined in the expert consensus in chapter 4. The validated wireless motion analysis system outlined in chapter 6 is used in conjunction with timings data to determine upper limb movement count and magnitude of linear acceleration (MLA) for each surgeon during the operation. Patient-specific outcome metrics include validated general health and procedure-specific patient-reported outcome measures (PROMs), post-operative radiographic analysis, and blood loss/transfusion requirements. Institutional outcome metrics include the post-operative patient length of stay, and the incidence of re-admission or re-operation within 30 days of the index procedure.

8.2 Study A: Construct validation study of intra-operative performance metrics and patient outcomes in primary elective total hip replacement.

8.2.1 Aims

The primary research question is to determine if any measurable significant differences exist in technical skills performance metrics of surgeons during primary elective THR, and both patient and institutional outcome metrics following this operation in relation to the lead surgeon grade. Analysis of these surgeon, patient, and institutional outcome metrics allow an expert (consultant) level of outcome metrics to be established in primary elective THR, which may be used as a benchmark against which to assess surgical trainee performance.

8.2.2 Methods

Study design

This is a prospective observational study.

Sponsor

The University of Oxford.

Funder

The Dinwoodie Charitable Company.

Ethical Approval and Study Registration

This study was conducted under ethical approval from the NHS Health Research Authority (NHS REC/HRA reference: 19/SC/0492; IRAS application number: 270167), and the Clinical Trial and Research Governance (CTRG) Department of the University of Oxford (reference: 14471). This study was registered on clinicaltrials.gov: ID NCT04267172. Trust management approval was obtained from both NHS Hospital recruitment centres (Appendix E).

Recruitment Centres

Two recruitment centres were used in this study:

1) The Nuffield Orthopaedic Centre, Oxford University Hospitals NHS Foundation Trust
2) Wycombe General Hospital, Buckinghamshire Healthcare NHS Trust

Power calculation

An online sample size calculator was used to determine the number of participants required to power this study. (313, 314) Using an α value=0.05, β value=0.2 a total of 25 primary THR cases are required in each surgeon group to detect a 15% difference in operative times, and 57 cases are required in each surgeon group to detect a 10% difference in operative times (based on a mean StR operative time of 84.3minutes, SD 16). (23)

Surgeon Participants

The surgeon participants recruited into this study were divided into three groups depending upon their grade. Consultant orthopaedic surgeons (consultants) represent the 'expert' group, senior orthopaedic arthroplasty fellows (fellows) represent the 'intermediate' group, and orthopaedic specialty trainees (StRs) represent the 'junior' group. The recruitment strategy for surgeon participants is outlined within the study protocol (Appendix section E.4). The criteria for surgeon participation in this study are:

Inclusion criteria:

- The participant is willing and able to give informed written consent for participation.
- Healthy adults aged 18 years or above.
- Surgeon participants must be either: employed as a consultant orthopaedic surgeon; senior arthroplasty fellow; or enrolled as an orthopaedic specialty trainee within a recognised higher surgical training programme.
- Surgeon participants must be working clinically at either of the recruitment centres over the study period.

Exclusion Criteria:

- Participant is unwilling, or unable to provide written informed consent.

All surgeon participants were given a study information sheet prior to providing written informed consent (Appendix E). All specialty registrars recruited into this study were also recruited into the studies outlined in chapter 7 and had previously been randomised to receive standard (control group), or additional simulation-based (intervention group) training. This randomisation is not directly relevant to the findings of this study but is pertinent to study B of this chapter.

Patient Participants

The criteria for patient participation in this study are:

Inclusion Criteria:

- Adult patients (aged 18 years or above) diagnosed with primary hip osteoarthritis who have been listed for elective primary THR within either of the NHS recruitment centres.
- Operation performed by a surgeon participant as lead surgeon during the study period.

Exclusion Criteria:

- Patients with complex hip pathology (e.g., previous trauma, hip dysplasia, infection).
- Patients who have had previous surgery on their affected hip.

All patient participants were given a study information sheet prior to providing written informed consent (Appendix E).

Protocol for Intra-Operative Data Collection

Details of the wireless inertial measurement unit (IMU) sensors (MBIENTLAB Inc., San Francisco, CA, USA) and intra-operative protocol for data collection used in this study are outlined in chapter 6.5. The timings of each pre-defined step of the operation were recorded by the lead researcher. Data collection was started at knife to skin and stopped when the dressing has been applied to the wound.

Outcome Metrics

Surgeon-specific, patient-specific, and institutional outcome metrics were recorded. The surgeon-specific outcome metrics are reported for the operation in its entirety, and in relation to each step of a primary THR. (174)

Surgeon-specific:

1) **Time**

   The timings data recorded intra-operatively allows synchronisation of surgeon motion data obtained via the IMU sensors throughout the steps of the operation.

2) **Movement count**

   Right hand, left hand, and the sum of both hand movements obtained from analysis of wireless IMU data as described in chapter 6. The number of mallet blows recorded for acetabular cup impaction (in uncemented and hybrid THR fixation), and femoral broaching (all implant fixations) is reported using the validated methodology described in chapter 6.

3) **Magnitude of linear acceleration (MLA)**

   Right- and left-hand movement MLA obtained from analysis of IMU data as described in chapter 6. The median MLA of mallet blows recorded for acetabular cup impaction (in uncemented and hybrid THR fixation), and femoral broaching (all implant fixation) are reported using to the validated methodology described in chapter 6.

Patient-specific:

1) Patient-reported outcome measures (PROMs)

The Oxford Hip Score (OHS) and EQ-5D 5L are validated PROMs, which are routinely collected following elective THR. (319, 320, 321, 322, 323) (Appendix E). PROMs were collected pre-operatively on the day of surgery, and between 3-4 months post-operatively over the telephone. The OHS is a 12-question hip joint specific PROM, with each question scored from 0-4 points (total 48 points), with a higher score indicating better hip joint function. The EQ-5D 5L is a general health-related quality of life PROM, with 5 domains (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression), in addition to a visual analogue scale (VAS) for patients to self-rate their overall health. Each domain has 5 levels, with a higher level indicating poorer function. The VAS is scored on a scale of 0-100, with a higher score indicating better overall health.

2) Radiographic analysis

Analysis of adequate post-operative pelvis radiographs allowed the following metrics to be measured:

- *Acetabular Cup Inclination (RI)*
- *Acetabular Cup Anteversion (RA) (114, 324)*
- *Leg length discrepancy (RLLD) (325)*
- *Femoral Stem Alignment (RFSA)*
- *Barrack & Harris Femoral Cementing Grade (142)*

The methodology for assessing acetabular cup inclination, femoral stem alignment, radiological leg length discrepancy, and femoral cementation have been outlined in chapter 2. The Lewinnek method for calculating acetabular cup anteversion is used. (114, 324)

3) Blood loss & transfusion requirements

The on-table blood loss (OTBL) was calculated for every case, and the incidence of blood product transfusions identified using electronic patient records. Pre- and post-operative laboratory full blood count (FBC) reports within 24 hours of surgery were used to determine the haemoglobin (Hb) concentration (g/dL) across the peri-operative period.

Institutional:

1) **Length of stay**

   The in-patient length of stay (LOS) was calculated for each patient using continuous integers of single days from the day of admission (day 0) to the day of discharge.

2) **Re-admission and re-operation within 30 days**

   The incidence of re-admission to the same hospital for any reason, and re-operation on the same hip being replaced within 30 days of the index procedure were identified using patient records.

Data Processing and Statistical Analysis

Statistical analysis was performed for each outcome metric between the three groups of surgeons (consultants, fellows, and StRs). Analysis was performed on the surgeon-specific outcome measures for the overall operation, and for each defined step. Normality of data distribution is not assumed, and non-parametric statistical tests are used. The Kruskal-Wallis test is be used to determine any significant differences between the three groups in outcome metrics measured using continuous data (time, movement counts, MLA, OHS, EQ-5D VAS, RI, RA, RLLD, RFSA, OTBL, Hb, and LOS), and Pearson's Chi-squared test (χ^2) is used to determine any significant differences in categorical outcome metrics (EQ-5D questions 1-5, incidence of transfusion, femoral cementation grade, and re-operation/re-admission). Following a significant Kruskal-Wallis test, Dunn's test of multiple comparisons was used to determine any pairwise significant differences between groups. Mean and standard deviations are used for descriptive statistics. American Society of Anesthesiologist (ASA) physical status grades were re-classified into two groups for reporting demographics. These groups represented healthy patients or those with mild systemic disease (ASA I/II), and those with severe systemic disease which may threaten life (ASA III/IV). Continuous age and body mass index (BMI) data was also categorized for tabulation and visualization purposes. Missing or omitted data is not included in the statistical analysis but is recorded in data tables as 'unknown'. Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The significance threshold was set at 0.05 for all statistical analysis, and data visualisation is presented for significant findings.

8.2.3 Results

A total of 23 surgeons and 220 patient participants were recruited between February 2019 and February 2022. Within the 23 surgeon participants, there were eight consultants who collectively performed a total of 76 THRs; eight fellows who collectively performed a total of 92 THRs; and seven StRs who collectively performed a total of 52 THRs. All surgeon participants except for a single StR were male (95.6%), and 19 were right-handed (82.6%). The number of THR recorded for each surgeon ranged from one to 26 (median=7, mean=9.6). Within the 220 patient participants, 199 (90.5%) were recruited from the Nuffield Orthopaedic Centre, and 21 (9.5%) from Wycombe General Hospital. Overall, 172 (78.2%) consented for use of their personal medical data, including electronic patient records (EPR) radiographs, and blood results.

8.2.3.1 Implant fixation

Hybrid implant fixation (cemented femoral stem with uncemented acetabular cup) was the most used, representing 65.5% (n=144) of all cases. This was followed by all uncemented implants, representing 24.1% of cases (n=53), and all cemented implants representing 10.5% of cases (n=23). There was no significant difference in implant fixation in relation to surgeon grade (p=0.076).

Table 8-1: THR implant fixation in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Implant Fixation					0.076
Hybrid	144 (65.5%)	46 (60.5%)	62 (67.4%)	36 (69.2%)	
Uncemented	53 (24.1%)	26 (34.2%)	18 (19.6%)	9 (17.3%)	
Cemented	23 (10.5%)	4 (5.3%)	12 (13.0%)	7 (13.5%)	

[1] n (%)

[2] Pearson's Chi-squared test

8.2.3.2 Patient demographics

Most patients were female (69.5%, n=153), and a significant difference was observed in the distribution of genders according to surgeon grade (p=0.022). This was due to a higher proportion of female patients within the StR group (84.5%), in comparison to the fellow (63.0%), or consultant groups (67.1%). The mean patient age was 67.8 years old, and a significant difference was observed in patient age according to surgeon grade (p=0.00043). Consultants were observed to operate on significantly younger patients in comparison to StRs (p=0.00037) and fellows (p= 0.0016). The mean body mass index (BMI) was 28.9kg/m^2. No significant differences were observed in BMI according to surgeon grade. The median American Society of Anesthesiologist (ASA) physical status grade was 2. A significant difference was observed in ASA grade according to surgeon grade (p=0.029), with consultants operating on a higher proportion of ASA 1 patients (14.8%) and lower proportion of ASA 2 patients (67.2%) in comparison to fellows (5.0% and 78.8% respectively) and StRs (0% and 75.0% respectively). However, no significant differences were observed in patient ASA category according to surgeon grade (p=0.5).

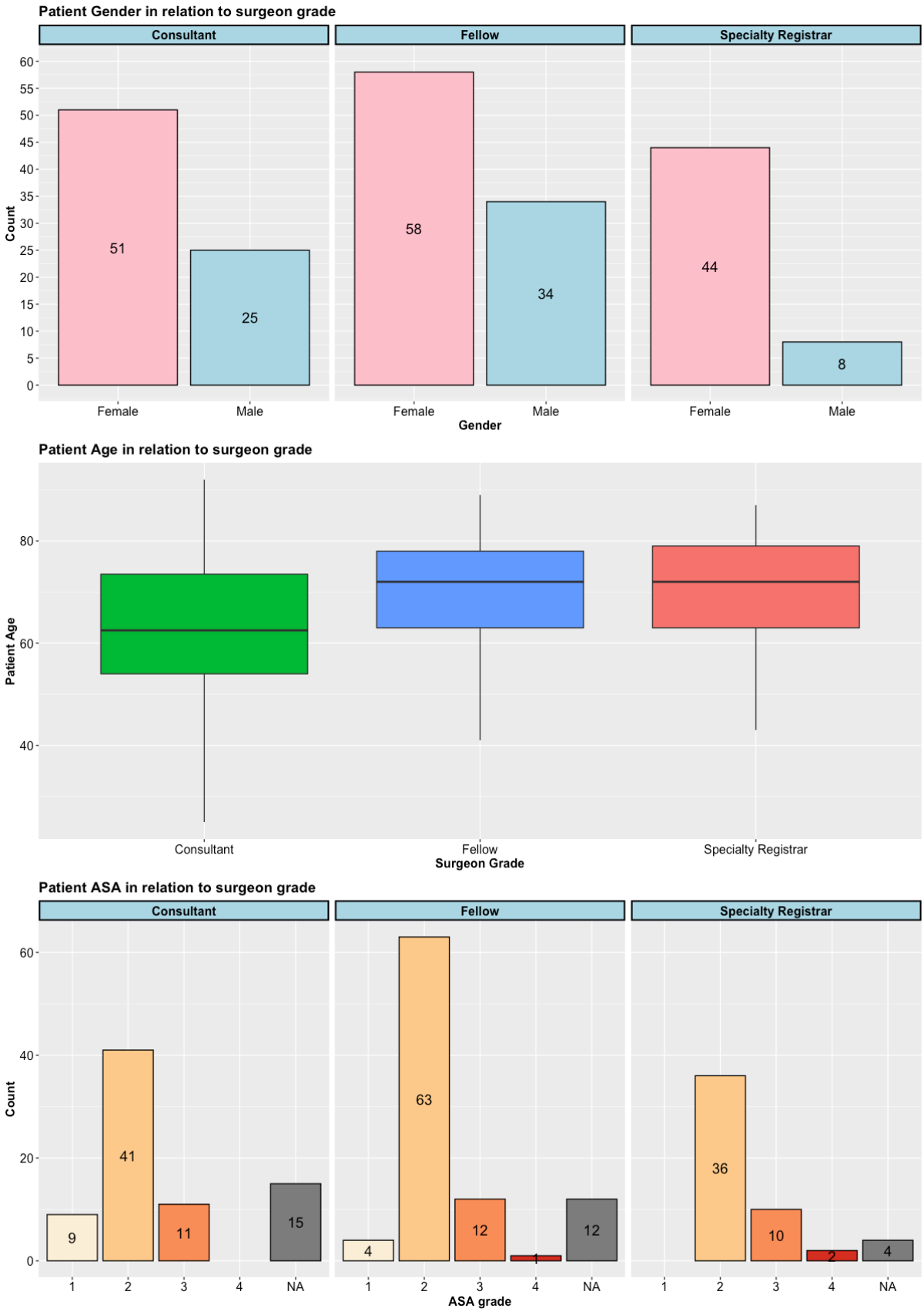
Table 8-2: Patient demographics in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Gender					
					0.022
Female	153 (69.5%)	51 (67.1%)	58 (63.0%)	44 (84.6%)	
Male	67 (30.5%)	25 (32.9%)	34 (37.0%)	8 (15.4%)	
Age					
Age	67.8 (12.1)	63.2 (13.4)	70.3 (10.6)	70.2 (10.8)	**<0.001**
Age Category					0.051
<40	2 (0.9%)	2 (2.6%)	0 (0%)	0 (0%)	
41-60	62 (28%)	30 (39%)	19 (21%)	13 (25%)	
61-80	126 (57%)	36 (47%)	60 (65%)	30 (58%)	
81-100	30 (14%)	8 (11%)	13 (14%)	9 (17%)	
BMI					
Body Mass Index	28.9 (5.5)	29.1 (5.7)	29.1 (5.3)	28.3 (5.4)	0.7
BMI Category					0.8
Normal	47 (21%)	16 (21%)	20 (22%)	11 (21%)	
Underweight	3 (1.4%)	1 (1.3%)	2 (2.2%)	0 (0%)	
Overweight	85 (39%)	27 (36%)	33 (36%)	25 (48%)	
Obese	78 (35%)	29 (38%)	33 (36%)	16 (31%)	
Morbidly Obese	7 (3.2%)	3 (3.9%)	4 (4.3%)	0 (0%)	
ASA					
ASA					**0.029**
1	13 (6.9%)	9 (14.8%)	4 (5.0%)	0 (0.0%)	
2	140 (74.1%)	41 (67.2%)	63 (78.8%)	36 (75.0%)	
3	33 (17.5%)	11 (18.0%)	12 (15.0%)	10 (20.8%)	
4	3 (1.6%)	0 (0.0%)	1 (1.2%)	2 (4.2%)	
Unknown	31	15	12	4	
ASA Category					0.5
1/2	153 (81.0%)	50 (82.0%)	67 (83.8%)	36 (75.0%)	
3/4	36 (19.0%)	11 (18.0%)	13 (16.2%)	12 (25.0%)	
Unknown	31	15	12	4	

[1] n (%)

[2] Pearson's Chi-squared test

Figure 8-1: Patient demographics in relation to surgeon grade.



8.2.3.3 Surgeon-specific metrics

1) Operative time

Overall

The mean operative time to perform a primary elective THR across all surgeon grades was 4228 seconds (1hour 10minutes 28seconds). A significant difference was observed in the mean total operating time according to surgeon grade (p=2.57e-08). Consultants were observed to have significantly faster mean operating times (3679 seconds, or 1hour 1minute 19seconds) in comparison to fellows (4422 seconds, or 1hour 13minutes 42seconds, p=7.66e-07) and StRs (4678 seconds, or 1hour 17minutes 58seconds, p=1.98e-07).

Steps

Significant differences were also observed in the mean operative time between groups for 12 out of the 16 steps: namely the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular reaming, acetabular cup implantation; femoral broaching; initial head trialling; femoral cement preparation; femoral cementing; definitive head trialling; and surgical closure (all $p<0.05$, see table 8-3).

Consultants were observed to have significantly faster mean times in comparison to both fellows and StRs during the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular reaming; acetabular cup implantation; and femoral cementing steps.

Consultants were observed to have significantly faster mean times in comparison to fellows but not StRs during the femoral broaching; femoral cement preparation; and surgical closure steps. Consultants were observed to have significantly faster mean times in comparison to StRs but not fellows during the initial and definitive head trialling steps. Fellows were observed to have significantly faster mean times in comparison to StRs during the hip dislocation; femoral neck osteotomy; acetabular cup implantation; initial and definitive head trialling steps.

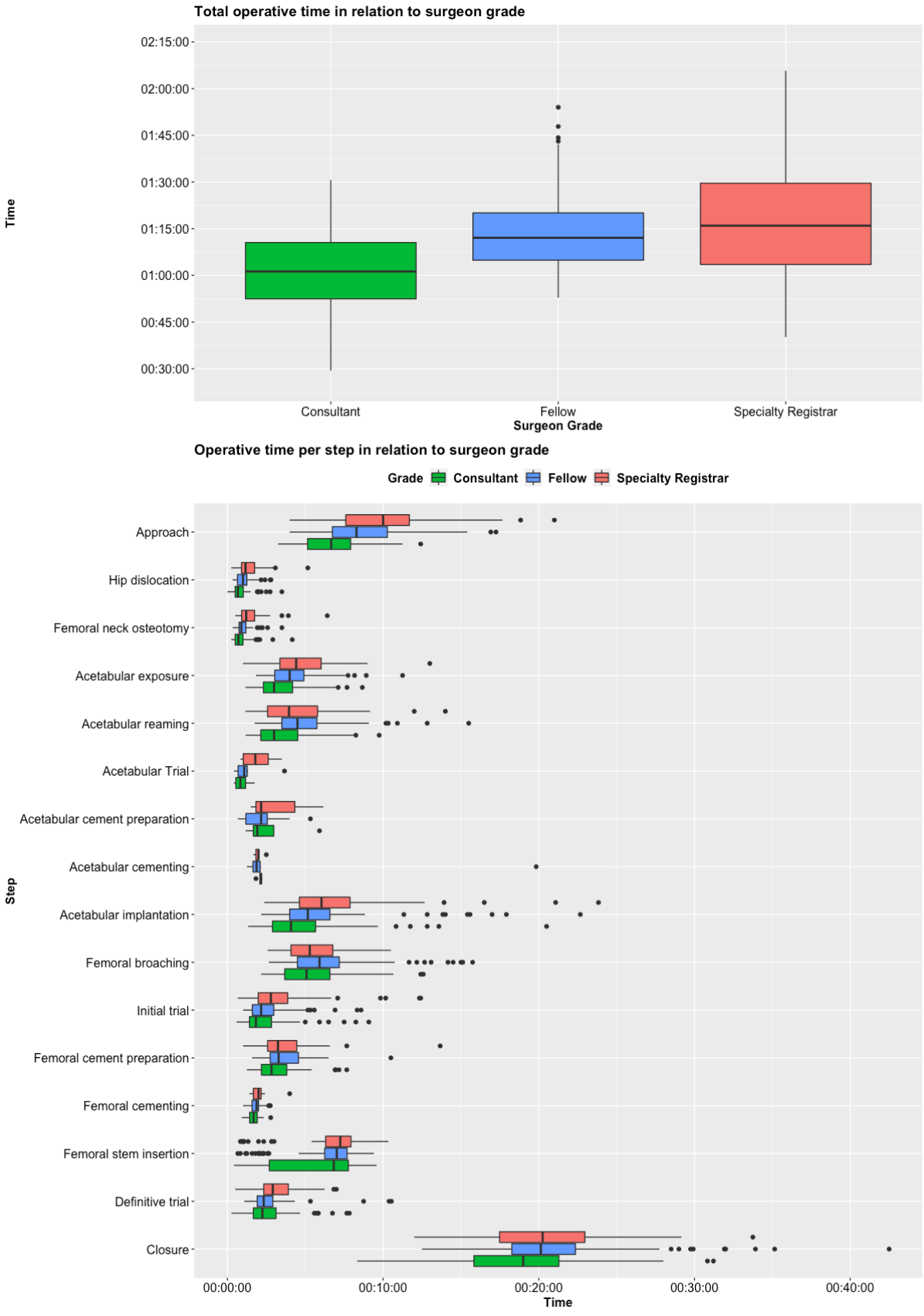
Table 8-3: Operative time in relation to surgeon grade.

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
			Total time		
Total Time (seconds)	4,228 (976)	3,679 (828)	4,422 (769)	4,678 (1,140)	**<0.001**
Unknown	1	1	0	0	
			Step time		
Approach	509 (185)	408 (120)	531 (165)	617 (224)	**<0.001**
Unknown	1	1	0	0	
Hip dislocation	62 (39)	52 (37)	60 (31)	81 (49)	**<0.001**
Unknown	1	0	0	1	
Femoral neck osteotomy	65 (44)	52 (37)	61 (29)	91 (61)	**<0.001**
Acetabular exposure	248 (112)	210 (97)	255 (99)	293 (134)	**<0.001**
Acetabular reaming	265 (141)	214 (115)	304 (141)	271 (154)	**<0.001**
Acetabular cup trialling	80 (57)	55 (29)	76 (62)	116 (66)	0.2
Unknown	199	69	84	46	
Acetabular step drill	158 (99)	164 (129)	138 (81)	190 (118)	0.7
Unknown	197	72	80	45	
Acetabular cementing	162 (225)	126 (11)	199 (313)	119 (16)	0.3
Unknown	197	72	80	45	
Acetabular implantation	357 (222)	296 (186)	364 (217)	433 (254)	**<0.001**
Femoral broaching	357 (154)	329 (139)	394 (179)	332 (110)	**0.040**
Unknown	1	1	0	0	
Initial trial	171 (121)	149 (108)	159 (94)	219 (162)	**0.002**
Unknown	28	14	10	4	
Femoral cement preparation	212 (97)	191 (91)	220 (79)	222 (127)	**0.022**
Unknown	53	26	18	9	
Femoral cementing	110 (25)	102 (23)	112 (25)	118 (26)	**0.005**
Unknown	53	26	18	9	
Femoral stem insertion	364 (154)	334 (174)	378 (135)	385 (152)	0.3
Definitive trial	174 (98)	170 (103)	163 (100)	197 (86)	**0.006**
Unknown	41	25	13	3	
Closure	1,213 (295)	1,140 (282)	1,266 (306)	1,224 (279)	**0.043**
Unknown	1	1	0	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-2: Operative time in relation to surgeon grade.



2) Movement count

Overall

The mean total movement count (combined right and left hands) to perform a primary elective THR across all surgeon grades was 150,505. A significant difference was observed in the mean total movement count according to surgeon grade (p=3.057e-08). Consultants were observed to have significantly less total movement counts (130,949) in comparison to fellows (154,425, p=5.48e-05) and StRs (172,115, p=1.42e-08). Fellows were also observed to have significantly fewer movement counts in comparison to StRs (p=0.029).

Steps

Significant differences were also observed in the mean total movement count between groups for 12 out of the 16 steps: namely the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular reaming, acetabular cup implantation; femoral broaching; initial head trialling; femoral cementing; femoral stem insertion; definitive head trialling; and surgical closure (all $p<0.05$, see table 8-4).

Consultants were observed to have significantly fewer movement counts in comparison to both fellows and StRs during the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular reaming; acetabular cup implantation; femoral cementing; and surgical closure steps.

Consultants were observed to have significantly fewer movement counts in comparison to fellows but not StRs during the femoral broaching step. Consultants were observed to have significantly fewer movement counts in comparison to StRs but not fellows during the initial head trialling; femoral stem insertion; and definitive head trialling steps. Fellows were observed to have significantly fewer movement counts in comparison to StRs during the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular cup implantation; initial head trialling; femoral stem insertion; and definitive head trialling steps.

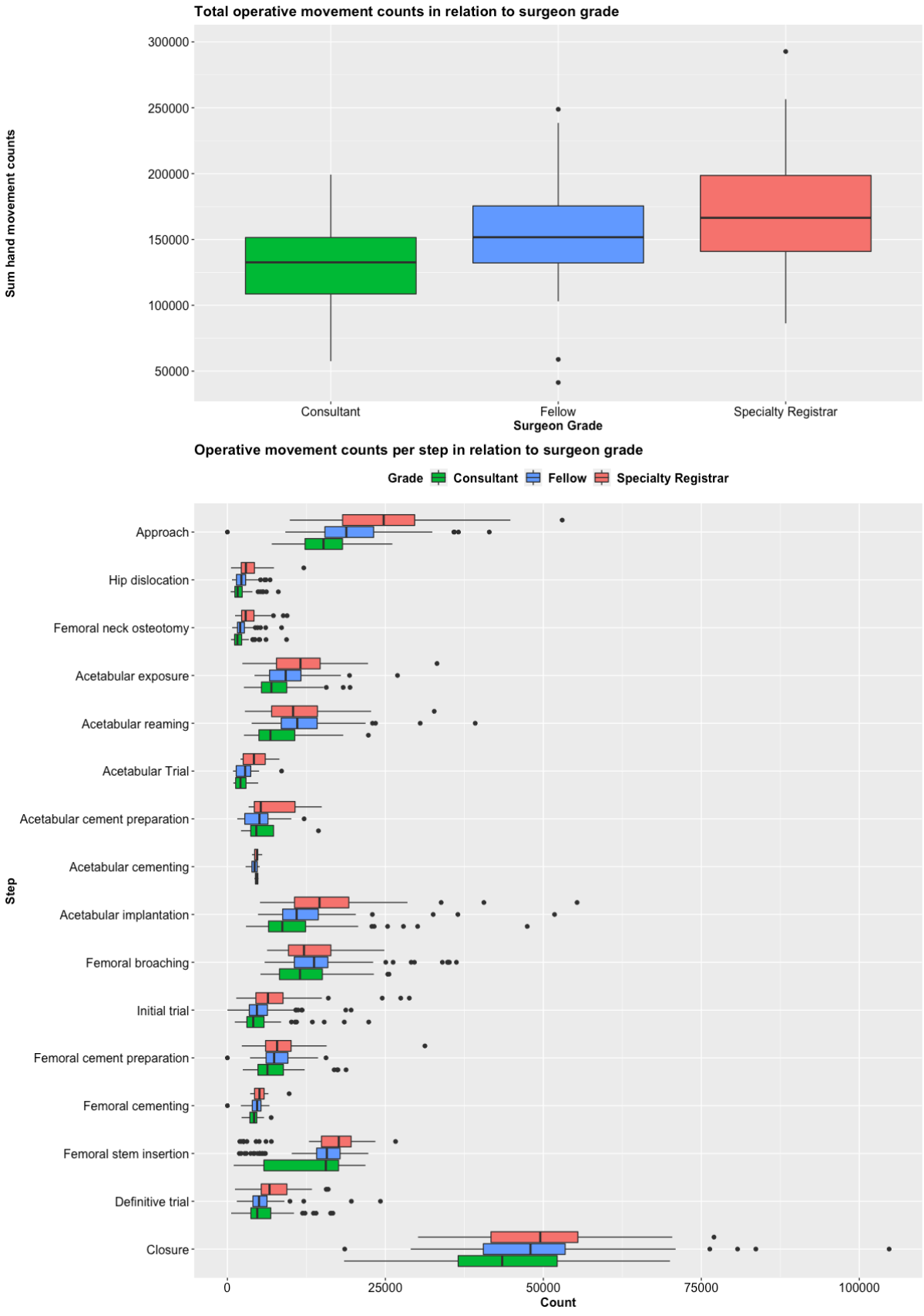
Table 8-4: Total movement counts in relation to surgeon grade.

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Total movement counts					
Total Movement Count	150,505 (38,190)	130,949 (30,923)	154,425 (33,063)	172,115 (42,176)	**<0.001**
Unknown	13	3	9	1	
Step movement counts					
Approach	19,827 (7,907)	15,436 (4,501)	20,040 (7,121)	25,343 (9,028)	**<0.001**
Unknown	23	7	16	0	
Hip dislocation	2,506 (1,595)	2,042 (1,440)	2,373 (1,288)	3,376 (1,917)	**<0.001**
Unknown	17	6	9	2	
Femoral neck osteotomy	2,498 (1,591)	1,997 (1,434)	2,333 (1,230)	3,484 (1,891)	**<0.001**
Unknown	13	3	9	1	
Acetabular exposure	9,662 (4,573)	7,968 (3,639)	9,767 (3,936)	11,917 (5,682)	**<0.001**
Unknown	13	3	9	1	
Acetabular reaming	10,513 (5,487)	8,370 (4,480)	11,986 (5,557)	11,154 (5,807)	**<0.001**
Unknown	12	3	8	1	
Acetabular implantation	12,929 (7,697)	10,938 (7,063)	12,587 (6,799)	16,383 (8,838)	**<0.001**
Unknown	17	3	12	2	
Acetabular step drill	6,295 (4,080)	6,429 (5,450)	5,464 (3,196)	7,643 (4,894)	0.6
Unknown	197	72	80	45	
Acetabular cementing	4,432 (571)	4,621 (289)	4,242 (641)	4,623 (530)	0.4
Unknown	198	72	81	45	
Acetabular cup trialling	3,312 (2,283)	2,343 (1,375)	3,237 (2,560)	4,540 (2,503)	0.2
Unknown	199	69	84	46	
Femoral broaching	13,509 (5,874)	12,201 (4,940)	14,930 (7,073)	13,100 (4,416)	**0.040**
Unknown	16	4	11	1	
Initial trial	6,116 (4,525)	5,304 (4,039)	5,554 (3,464)	8,011 (5,892)	**<0.001**
Unknown	45	17	22	6	
Femoral cement preparation	7,941 (3,682)	7,372 (3,800)	7,949 (2,614)	8,609 (4,839)	0.058
Unknown	63	27	25	11	
Femoral cementing	4,607 (1,161)	4,180 (949)	4,586 (1,214)	5,153 (1,102)	**<0.001**
Unknown	63	27	25	11	
Femoral stem insertion	14,120 (6,252)	12,704 (6,835)	14,451 (5,305)	15,617 (6,503)	**0.015**
Unknown	16	4	10	2	
Definitive trial	6,401 (3,647)	6,224 (3,930)	5,742 (3,452)	7,545 (3,404)	**0.001**
Unknown	55	26	24	5	
Closure	47,434 (12,055)	44,035 (10,787)	49,158 (13,158)	49,580 (10,989)	**0.016**
Unknown	18	4	11	3	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-3: Total movement counts in relation to surgeon grade.



3) Magnitude of linear acceleration (MLA)

Overall

The mean right- and left- hand MLA when performing a primary elective THR across all surgeon grades were 0.0016 and 0.0010m/s^2, respectively. A significant difference was observed in both right- and left- hand MLA according to surgeon grade (p=6.53e-10 and p=2.22e-08, respectively). Consultants were observed to have significantly increased right- and left-hand MLA (0.0016 and 0.0009m/s^2, respectively) in comparison to StRs (0.0008 and 0.0005m/s^2, respectively, p=3.47e-07 and p=0.0061), and significantly decreased right- and left-hand MLA in comparison to fellows (0.0022 and 0.0013m/s^2, respectively, p=0.0016 and p=6.83e-04). Fellows were observed to have significantly increased right- and left-hand MLA in comparison to StRs (p=8.35e-11 and p=4.51e-09).

Steps

Significant differences were also observed in the mean right- and left- hand MLA between groups for 11 out of the 16 steps: namely the surgical approach; hip dislocation; femoral neck osteotomy; acetabular exposure; acetabular reaming, acetabular cup implantation; femoral broaching; initial head trialling; femoral cement preparation; definitive head trialling; and surgical closure (all p<0.05, see table 8-5). A significant difference was also observed in the mean right- but not left- hand MLA between groups for the femoral stem insertion step.

Surgical approach

Consultants demonstrated significantly decreased right- and left-hand MLA in comparison to fellows but not StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Hip dislocation

Consultants demonstrated significantly increased right- and left-hand MLA in comparison to StRs, but not fellows. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Femoral neck osteotomy

Consultants demonstrated significantly decreased left- but not right-hand MLA compared to fellows, and significantly increased right- but not left-hand MLA in comparison to StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Acetabular exposure

Consultants demonstrated significantly decreased right- and left-hand MLA in comparison to fellows, and significantly increased right- and left-hand MLA in comparison to StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Acetabular reaming

Consultants demonstrated significantly increased right- and left-hand MLA in comparison to StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Acetabular cup implantation

Consultants demonstrated significantly increased right- and left-hand MLA in comparison to StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Femoral broaching

Consultants demonstrated significantly increased right- and left-hand MLA in comparison to StRs. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Initial head trialling

Consultants demonstrated but significantly increased right- and left-hand MLA in comparison to StRs. Fellows were observed to have significantly increased right- and left- hand MLA in comparison to StRs.

Femoral cement preparation

Consultants demonstrated significantly decreased right- and left-hand MLA in comparison to fellows. Fellows demonstrated significantly increased right- but not left- hand MLA in comparison to StRs.

Femoral stem insertion

Consultants demonstrated significantly increased right- but not left-hand MLA in comparison to fellows. Fellows demonstrated significantly increased right- but not left- hand MLA in comparison to StRs.

Definitive head trialling

Consultants demonstrated significantly decreased right- and left-hand MLA in comparison to fellows. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Surgical closure

Consultants demonstrated significantly decreased right- and left-hand MLA in comparison to fellows. Fellows demonstrated significantly increased right- and left- hand MLA in comparison to StRs.

Table 8-5: MLA of hand movements in relation to surgeon grade.

	Right hand					Left hand				
	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Median average over operation										
	0.0016 (0.0018)	0.0016 (0.0024)	0.0022 (0.0015)	0.0008 (0.0005)	**<0.001**	0.0010 (0.0007)	0.0009 (0.0007)	0.0013 (0.0008)	0.0005 (0.0004)	**<0.001**
Unknown	39	11	22	6		39	11	22	6	
Median average per step										
Approach	0.0005 (0.0005)	0.0004 (0.0004)	0.0007 (0.0006)	0.0003 (0.0003)	**<0.001**	0.0004 (0.0005)	0.0003 (0.0004)	0.0006 (0.0006)	0.0002 (0.0003)	**<0.001**
Unknown	25	7	17	1		26	7	18	1	
Hip dislocation	0.0030 (0.0086)	0.0028 (0.0037)	0.0044 (0.0127)	0.0009 (0.0017)	**<0.001**	0.004 (0.025)	0.003 (0.005)	0.007 (0.039)	0.001 (0.002)	**<0.001**
Unknown	16	6	8	2		17	6	9	2	
Femoral neck osteotomy	0.005 (0.007)	0.004 (0.005)	0.007 (0.008)	0.002 (0.004)	**<0.001**	0.005 (0.009)	0.003 (0.004)	0.008 (0.012)	0.002 (0.004)	**0.002**
Unknown	12	3	8	1		13	3	9	1	
Acetabular exposure	0.0033 (0.0033)	0.0030 (0.0025)	0.0045 (0.0042)	0.0015 (0.0014)	**<0.001**	0.0023 (0.0036)	0.0016 (0.0016)	0.0037 (0.0051)	0.0011 (0.0017)	**<0.001**
Unknown	12	3	8	1		13	3	9	1	
Acetabular reaming	0.004 (0.004)	0.005 (0.004)	0.005 (0.004)	0.001 (0.001)	**<0.001**	0.004 (0.006)	0.005 (0.006)	0.006 (0.008)	0.002 (0.002)	**<0.001**
Unknown	11	3	8	0		11	3	8	0	
Acetabular Trial	0.0038 (0.0033)	0.0035 (0.0027)	0.0058 (0.0041)	0.0021 (0.0023)	0.10	0.004 (0.005)	0.005 (0.007)	0.003 (0.003)	0.003 (0.005)	0.8
Unknown	202	70	86	46		202	70	86	46	
Acetabular cement preparation	0.0030 (0.0043)	0.0035 (0.0026)	0.0042 (0.0060)	0.0010 (0.0010)	0.2	0.0020 (0.0023)	0.0012 (0.0013)	0.0032 (0.0029)	0.0008 (0.0007)	0.3
Unknown	202	72	84	46		202	72	84	46	
Acetabular cementing	0.0024 (0.0052)	0.0010 (0.0010)	0.0044 (0.0075)	0.0006 (0.0005)	0.4	0.0006 (0.0007)	0.0006 (0.0003)	0.0010 (0.0008)	0.0003 (0.0003)	0.2
Unknown	202	72	84	46		202	72	84	46	
Acetabular implantation	0.006 (0.008)	0.007 (0.008)	0.008 (0.009)	0.002 (0.003)	**<0.001**	0.003 (0.005)	0.004 (0.005)	0.004 (0.004)	0.001 (0.003)	**<0.001**
Unknown	15	3	10	2		16	3	11	2	
Femoral broaching	0.013 (0.010)	0.016 (0.013)	0.013 (0.010)	0.009 (0.005)	**0.011**	0.009 (0.009)	0.009 (0.008)	0.009 (0.006)	0.008 (0.014)	**0.020**
Unknown	14	4	9	1		15	4	10	1	
Initial trial	0.007 (0.008)	0.009 (0.010)	0.008 (0.006)	0.004 (0.006)	**<0.001**	0.007 (0.015)	0.007 (0.009)	0.007 (0.007)	0.006 (0.026)	**<0.001**
Unknown	44	17	21	6		45	17	22	6	
Femoral cement preparation	0.007 (0.006)	0.006 (0.006)	0.008 (0.005)	0.005 (0.005)	**0.009**	0.004 (0.005)	0.003 (0.003)	0.005 (0.006)	0.004 (0.005)	**0.025**
Unknown	61	26	24	11		61	26	24	11	
Femoral cementing	0.0004 (0.0009)	0.0003 (0.0004)	0.0005 (0.0011)	0.0004 (0.0009)	0.060	0.0004 (0.0008)	0.0002 (0.0003)	0.0005 (0.0011)	0.0004 (0.0008)	0.4
Unknown	56	26	24	6		61	26	25	10	
Femoral stem insertion	0.005 (0.012)	0.007 (0.015)	0.005 (0.010)	0.002 (0.004)	**<0.001**	0.004 (0.020)	0.009 (0.033)	0.003 (0.008)	0.001 (0.003)	0.4
Unknown	13	3	9	1		14	3	10	1	
Definitive trial	0.004 (0.006)	0.003 (0.003)	0.006 (0.009)	0.003 (0.004)	**<0.001**	0.0028 (0.0039)	0.0024 (0.0032)	0.0037 (0.0051)	0.0018 (0.0020)	**0.003**
Unknown	54	26	24	4		54	26	24	4	
Closure	0.0011 (0.0015)	0.0007 (0.0006)	0.0017 (0.0021)	0.0006 (0.0005)	**<0.001**	0.0004 (0.0003)	0.0003 (0.0003)	0.0005 (0.0003)	0.0002 (0.0001)	**<0.001**
Unknown	16	3	11	2		16	3	11	2	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-4: Right hand MLA in relation to surgeon grade.

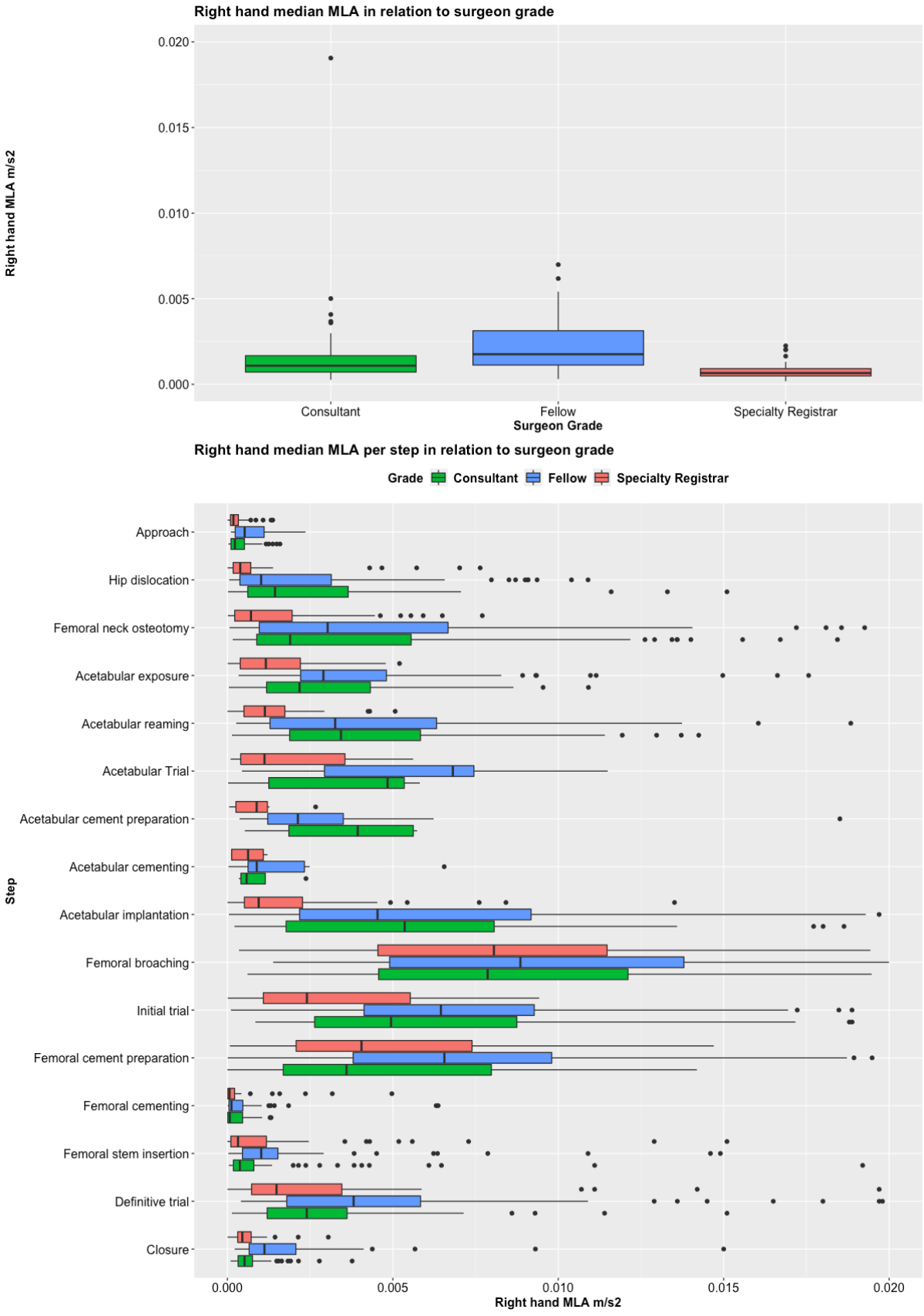
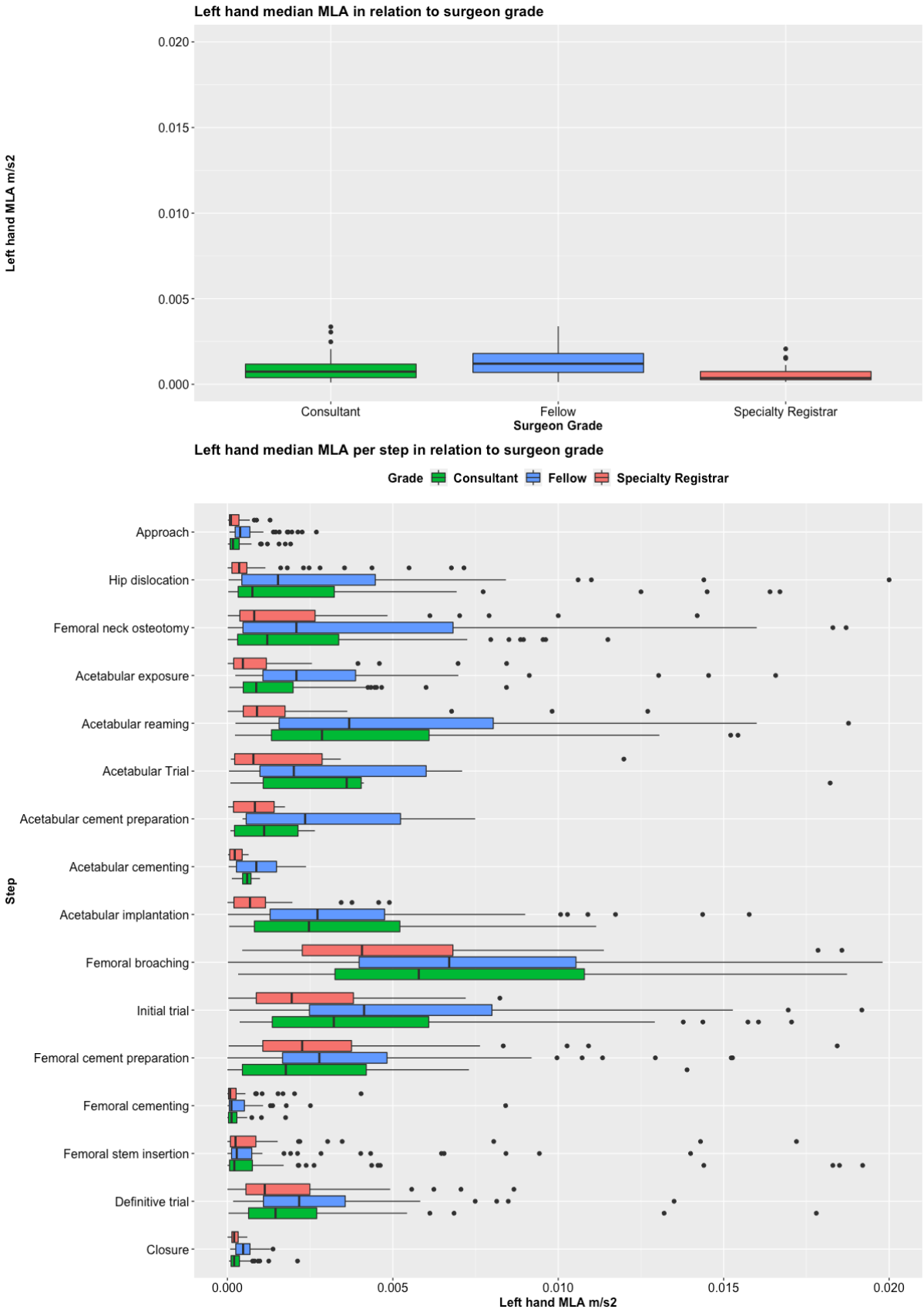


Figure 8-5: Left hand MLA in relation to surgeon grade.



4) Acetabular cup implantation and femoral stem broaching mallet blow count and MLA

The number and MLA value of each intra-operative mallet blow exceeding the 5g (49.03m/s^2) threshold of MLA during uncemented acetabular cup implantation and femoral canal broaching were identified using the signal processing methodology outlined in study C of chapter 6. The median of the total mallet blow MLA delivered during each operation was used as a surrogate marker for statistical analysis. The distribution of mallet blow MLA data was not normal on Shapiro-Wilk test for both uncemented acetabular cup implantation ($p<2.2e-16$) and femoral canal broaching, therefore median and IQR descriptive statistics are used for tabular data.

Acetabular cup implantation

Data for calculating the number and MLA of mallet blows when implanting an uncemented acetabular cup during a primary elective THR was available for 157 (71.4%) and 164 (74.5%) cases, respectively. The mean number of blows when implanting an uncemented acetabular cup and liner across all surgeon grades was 45. No significant difference was observed in the number of blows during acetabular cup implantation according to surgeon grade ($p=0.844$). The median MLA of blows across all surgeon grades was 2,475m/s^2. A significant difference was observed in the MLA of blows according to surgeon grade ($p=0.017$). Consultants demonstrated significantly reduced MLA during uncemented acetabular cup implantation (1,584m/s^2) in comparison to fellows (3,838m/s^2, $p=0.0046$), but not StRs (1,955m/s^2, $p=0.47$).

Femoral broaching

Data for calculating the number and MLA of mallet blows when broaching the femoral canal during a primary elective THR was available for 200 (90.9%) and 203 (92.3%) cases, respectively. The mean number of blows when broaching the femur across all surgeon grades was 130. A significant difference was observed in the number of blows during femoral broaching according to surgeon grade ($p=0.01$). Consultants demonstrated significantly fewer blows ($n=109$) in comparison to fellows ($n=153$, $p=0.0026$), but not StRs ($n=122$, $p=0.3$). The median MLA of blows across all surgeon grades was 349m/s^2. A significant difference was observed in the MLA of blows according

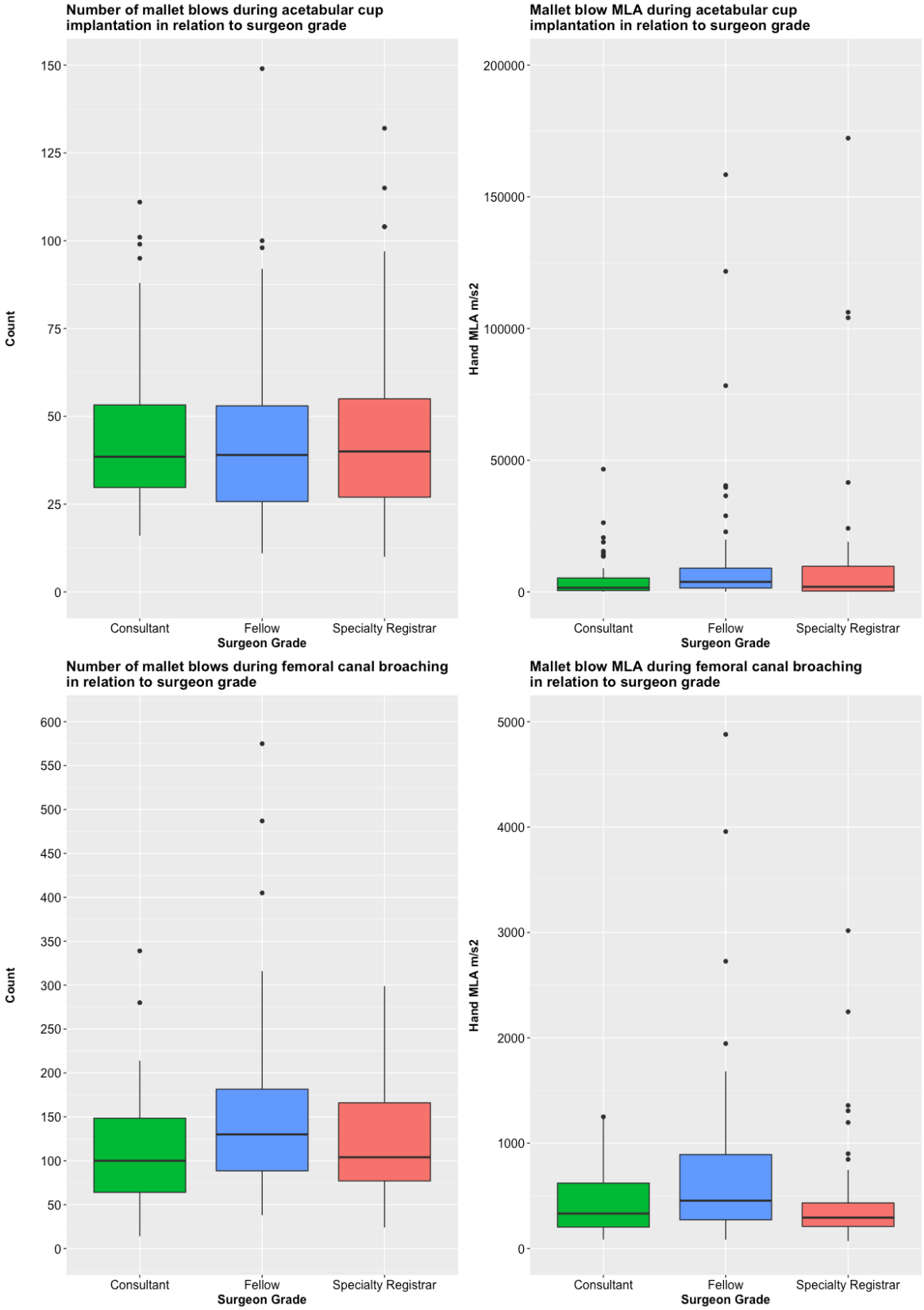
to surgeon grade (p=0.034). Consultants demonstrated significantly reduced MLA during femoral broaching (332m/s^2) in comparison to fellows (455m/s^2, p=0.0049), but not StRs (297m/s^2, p=0.56). StRs were also observed to have significantly reduced MLA during femoral broaching in comparison to fellows (p=0.017).

Table 8-6: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to surgeon grade.

	Impaction Count					Linear deceleration (ms2)				
	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]	**Overall**, N = 220[3]	**Consultant**, N = 76[3]	**Fellow**, N = 92[3]	**Specialty Registrar**, N = 52[3]	**p-value**[2]
Acetabular Cup Impaction										
	45 (25)	45 (22)	44 (25)	49 (33)	0.8	2,475 (724,7,951)	1,584 (528,5,320)	3,838 (1,489,9,044)	1,955 (322,9,762)	**0.017**
Unknown	63	12	28	23		56	9	25	22	
Femoral Stem Broaching										
	130 (80)	109 (62)	153 (96)	122 (66)	**0.010**	349 (220,685)	332 (204,621)	455 (273,892)	297 (210,481)	**0.034**
Unknown	20	4	13	3		17	4	12	1	

[1] Mean (SD)
[2] Kruskal-Wallis rank sum test
[3] Median (25%,75%)

Figure 8-6: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to surgeon grade.



8.2.3.4 Patient-specific metrics

1) Patient-reported outcome measures (PROMs)

Oxford Hip Score (OHS)

Data for calculating the pre- and post-operative OHS was available for 172 (78.2%) cases, and 158 (71.8%) cases, respectively. The mean pre-operative OHS across all surgeon grades was 17, and no significant difference was observed according to surgeon grade (p=0.23). The mean post-operative OHS across all surgeon grades was 41, and no significant difference was observed according to surgeon grade (p=0.34).

Table 8-7: Oxford Hip Scores in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Baseline OHS					
	17 (8)	16 (8)	18 (9)	15 (8)	0.2
Unknown	48	25	19	4	
3-month follow-up OHS					
	41 (6)	41 (7)	40 (7)	40 (6)	0.3
Unknown	62	30	24	8	
Change in OHS					
	24 (9)	25 (8)	22 (10)	25 (9)	0.2
Unknown	63	30	24	9	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

EQ-5D 5L VAS

Data for calculating the pre- and post-operative EQ-5D 5L was available for 172 (78.2%) cases, and 158 (71.8%) cases, respectively. The mean pre-operative EQ-5D 5L VAS across all surgeon grades was 63, and no significant difference was observed according to surgeon grade (p=0.11). The mean post-operative EQ-5D 5L VAS across all surgeon grades was 78, and no significant difference was observed according to surgeon grade (p=0.26).

Table 8-8: EQ-5D 5L VAS in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Baseline EQ5D VAS					
	63 (21)	64 (22)	66 (19)	57 (22)	0.11
Unknown	48	25	19	4	
3-month follow-up EQ5D VAS					
	78 (17)	78 (19)	81 (15)	75 (18)	0.3
Unknown	62	30	24	8	
Change in EQ5D VAS					
	16 (17)	13 (20)	16 (17)	19 (15)	0.2
Unknown	62	30	24	8	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

EQ-5D 5L Domains

No significant difference was observed according to surgeon grade in relation to the pre-operative EQ-5D 5L mobility (p=0.12), self-care (p=0.3), usual activities (p=0.076), pain/discomfort (p=0.3), or anxiety/depression (p=0.5) domains. (Appendix E). No significant difference was observed according to surgeon grade in relation to the post-operative EQ-5D 5L mobility (p=0.7), self-care (p=0.5), usual activities (p=0.064), pain/discomfort (p=0.8), or anxiety/depression (p=0.4) domains. (Appendix E). No significant difference was observed according to surgeon grade in relation to the change in EQ-5D 5L mobility (p=0.6), self-care (p=0.5), usual activities (p=0.32), pain/discomfort (p=0.17), or anxiety/depression (p=0.7) domains. (Appendix E).

2) Radiographic analysis

Radiographic analysis was performed on 168 (76.4%) cases. Patients did not provide consent in 48 cases (21.8%), and 4 patients (1.8%) did not have adequate pre- and/or post-operative pelvic radiographs.

The mean radiographic acetabular cup inclination (RI) across all surgeon grades was 41.9°. No significant difference was observed in the RI according to surgeon grade (p=0.7). The mean radiographic acetabular cup anteversion (RA) across all surgeon grades was 18.0°. No significant difference was observed in the RA according to surgeon grade (p=0.3). The mean radiographic leg length discrepancy (RLLD) across all surgeon grades was 1.9mm. No significant difference was observed in the RLLD according to surgeon grade (p=0.6). The mean radiographic femoral stem alignment (RFSA) across all surgeon grades was 1.6° varus. A significant difference was observed in the RFSA according to surgeon grade (p=0.025). Consultants were observed to have significantly higher mean RFSA (2.0° varus) in comparison to StRs (1.2° varus), but not fellows (1.5° varus). The most common Barrack & Harris femoral cementing grade across all surgeon grades was B (n=80, or 63%), indicating radiolucent lines covering up to 50% of the mantle. No significant difference was observed in the Barrack & Harris grade according to surgeon grade (p=0.4).

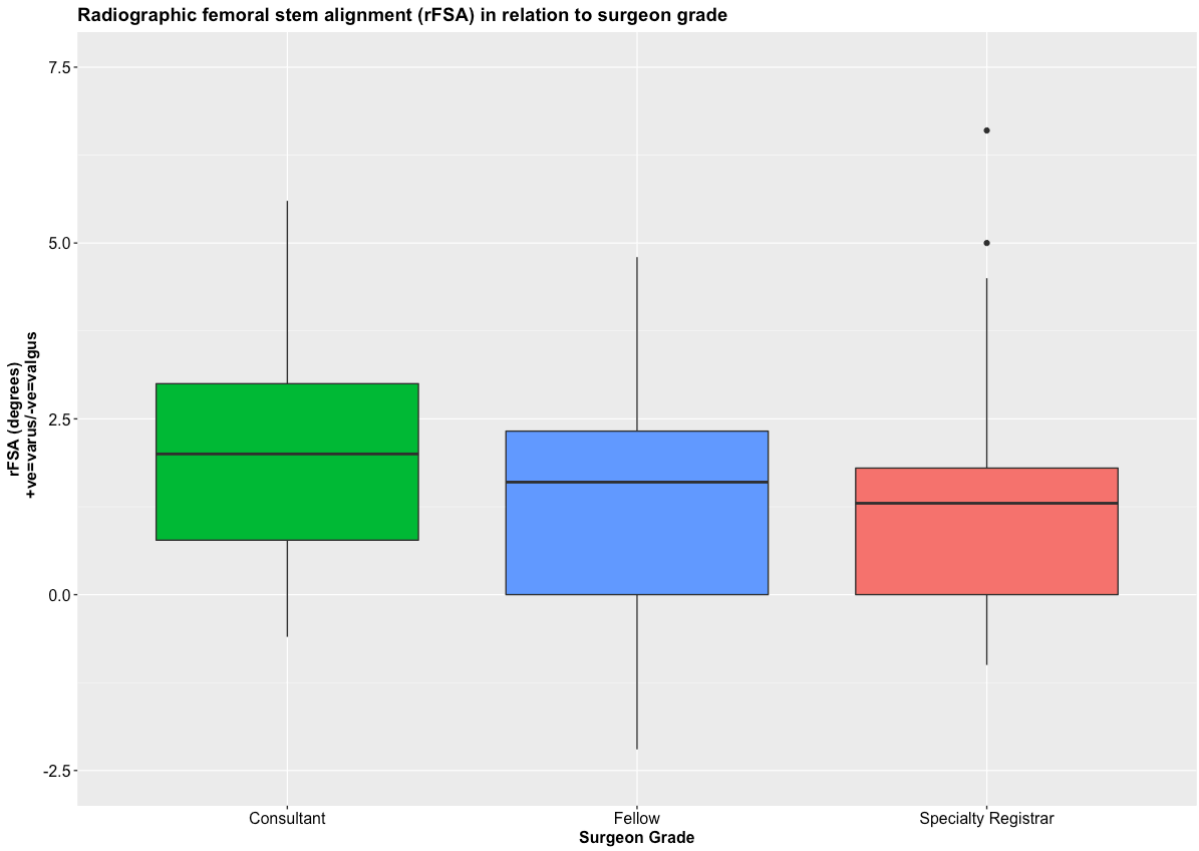
Table 8-9: Radiographic parameters in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Acetabular Cup Inclination (degrees)					
	41.9 (7.8)	41.3 (7.5)	41.9 (8.4)	42.7 (7.2)	0.7
Unknown	52	28	20	4	
Acetabular Cup Anteversion (degrees)					
	18.0 (7.5)	19.3 (9.1)	18.2 (6.3)	16.6 (7.5)	0.3
Unknown	52	28	20	4	
Radiological Leg Length Discrepancy (mm)					
	1.9 (6.4)	1.4 (7.3)	1.9 (6.3)	2.4 (5.8)	0.6
Unknown	53	28	20	5	
Radiological Femoral Stem Alignment (degrees)					
	1.6 (1.6)	2.0 (1.6)	1.5 (1.5)	1.2 (1.7)	**0.025**
Unknown	52	28	20	4	
Barrack & Harris Femoral Cementation Grade					
					0.4
A	33 (26%)	8 (25%)	18 (32%)	7 (18%)	
B	80 (63%)	22 (69%)	33 (59%)	25 (64%)	
C	14 (11%)	2 (6.2%)	5 (8.9%)	7 (18%)	
Unknown	93	44	36	13	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-7: Radiographic femoral stem alignment (rFSA) in relation to surgeon grade.



3) Blood loss & transfusion requirements

The mean pre-operative Hb across all surgeon grades was 135g/dL. No significant difference was observed in the pre-operative Hb according to surgeon grade (p=0.2). Intravenous tranexamic acid was administered to all patients immediately pre-operatively in the anaesthetic room. The mean post-operative Hb across all surgeon grades was 112g/dL. No significant difference was observed in the post-operative Hb according to surgeon grade (p=0.2). The mean on-table blood loss (OTBL) across all surgeon grades was 316mls. No significant difference was observed in the OTBL according to surgeon grade (p>0.9). Only three patients (1.7%) received a blood transfusion.

Table 8-10: Blood loss & transfusion requirements in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Pre-op Hb (g/dL)					
	135 (14)	137 (13)	134 (13)	133 (15)	0.2
Unknown	48	25	19	4	
Post-op Hb (g/dL)					
	112 (15)	114 (14)	112 (14)	109 (16)	0.2
Unknown	57	31	20	6	
Change in Hb (g/dL)					
	-23 (9)	-23 (8)	-23 (9)	-24 (10)	>0.9
Unknown	57	31	20	6	
On-Table Blood Loss (mls)					
	316 (187)	316 (202)	322 (190)	304 (161)	>0.9
Unknown	10	5	2	3	
Post-op transfusion					
	3 (1.7%)	1 (2.0%)	1 (1.4%)	1 (2.1%)	>0.9
Unknown	48	25	19	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

8.2.3.5 Institutional metrics

Length of stay, re-admissions, and re-operations

The mean LOS across all surgeon grades was 3.13 days. A significant difference was observed in the LOS according to surgeon grade (p=0.038). Consultants were observed to have significantly shorter mean LOS (2.41 days) in comparison to fellows (3.6 days, p=0.014), but not StRs (3.19 days, p=0.057). The incidence of all cause re-admissions to hospital within 30 days of the index operation was 5.2% (n=9), and no significant difference was observed in the incidence of re-admissions according to surgeon grade (p=0.6). The incidence of re-operations within 30 days of the index operation was 0.6% (n=1), which was an isolated case of early culture positive prosthetic joint infection which required a debridement and exchange of modular components.

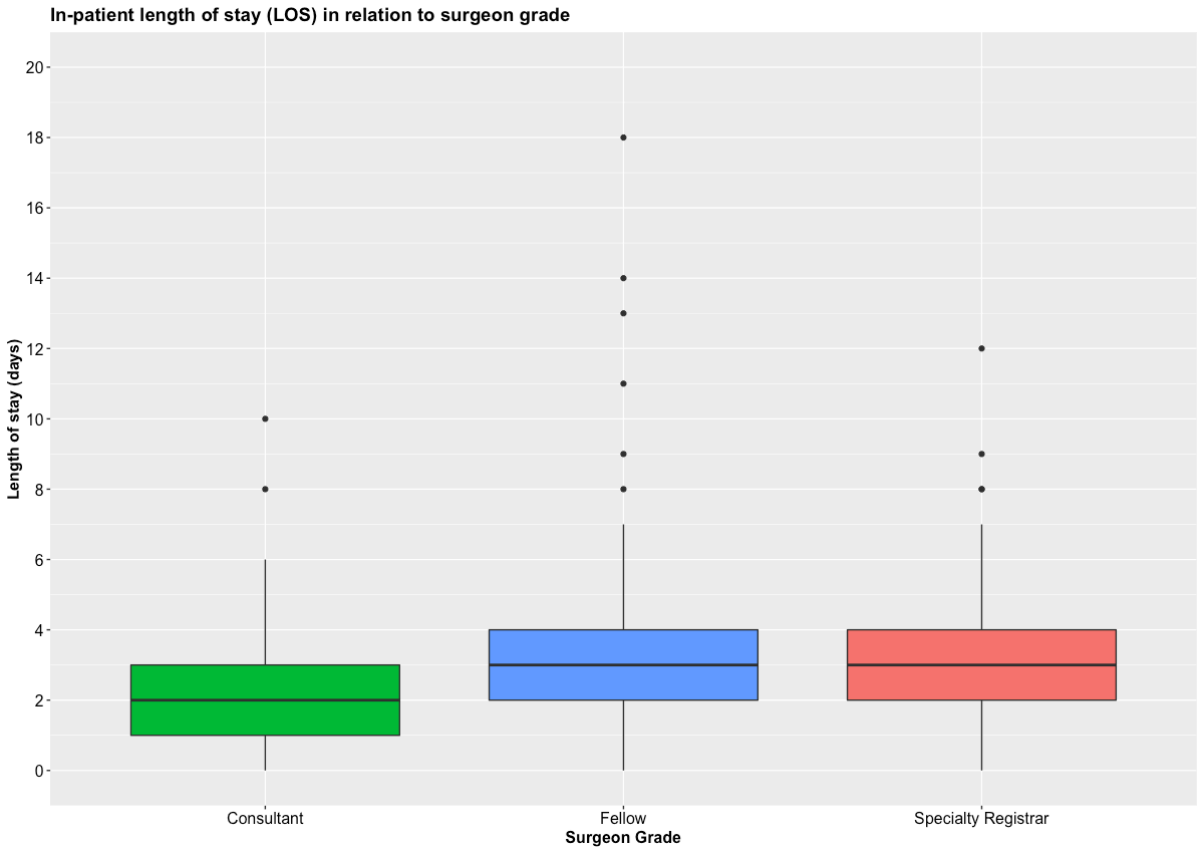
Table 8-11: Length of stay, re-admissions, and re-operations in relation to surgeon grade.

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**[2]
Length of Stay (days)					
	3.13 (2.73)	2.41 (2.11)	3.60 (3.21)	3.19 (2.41)	**0.038**
Unknown	49	25	20	4	
Re-admission to Hospital within 30days					
	9 (5.2%)	3 (5.9%)	5 (6.8%)	1 (2.1%)	0.6
Unknown	48	25	19	4	
Re-operation within 30days					
	1 (0.6%)	0 (0%)	1 (1.4%)	0 (0%)	>0.9
Unknown	48	25	19	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-8: In-patient length of stay in relation to surgeon grade.



8.3 Study B: Randomised controlled pilot study assessing the impact of simulation training on performance metrics and patient outcomes in primary elective total hip replacement.

8.3.1 Aims

The primary research question is to determine if additional simulation training can improve the intra-operative performance metrics of orthopaedic StRs during a primary elective THR, or patient and institutional outcome metrics following primary THR. Secondary outcome measures include assessing the impact of the number of years of specialty surgical training; the number of primary THR performed as first surgeon; and the procedural-based assessment (PBA) level of surgical trainees on the same outcome metrics.

8.3.2 Methods

The sponsor, funding, ethical approval and study registration, recruitment centres, protocol for data collection, and outcome metrics used in this study are the same as described in study A (section 8.2.2). The only additional surgeon-specific outcome metrics collected in this study are the Procedural-Based Assessment (PBA) global rating scale. (16, 54) This assessment was completed by the consultant supervising the StR immediately after each operation.

Study design

This is a prospective randomised controlled study.

Surgeon and Patient Participants

The surgeon participants in this study are the StRs recruited into study A of this chapter, and the respective patients for which these surgeons performed supervised primary elective THR. These surgeon participants represent a subset of the 34 StRs recruited into the laboratory-based studies in

chapter 7 and had previously been randomised to receive either standardised training (control group), or additional simulation-based training (intervention group) as part of recruitment into these previous studies. The intervention tested in this study is the simulation-based training module outlined in chapter 5.2. Details on group randomisation strategy may be found in section 7.3.2.

The training profiles and surgical logbook data of these StRs were collected for study B in chapter 7 and were used for data analysis in this study. This data included each StRs post-graduate year (PGY) in specialty training, and the total number of primary THR performed as first surgeon for each surgical trainee (STS-THR). The PGY was grouped into three categories for analysis as follows: early (PGY 1-2); middle (PGY 3-4), and final years (PGY 5-6). These categories reflect the waypoints in training outlined in the current JCST guidelines for higher trauma & orthopaedic surgical training. (84) The STS-THR were also grouped into three categories for analysis as follows: 0-19; 20-39; and greater than 40. These categories were selected in line with 2017/2018 JCST guidelines, which stipulate that a minimum of 40 primary THR should be achieved by trainees as first surgeon prior to completion of training.

Power calculation

An online sample size calculator was used to determine the number of participants required to power this study. (313, 314) Using an α value=0.05, β value=0.2 a total of 25 primary THR cases are required in each StR surgeon group (control/intervention) to detect a 15% difference in operative time. This is based on a mean StR operative time of 84.3minutes, SD 16. (23)

Data Processing and Statistical Analysis

Statistical analysis was performed for each outcome metric in relation to the StR group (control/intervention); PGY category (1/2, 3/4, or 5/6), the total number of STS-THR (0-19, 20-39, or >40), and the PBA level achieved following completion of each primary THR during this study (rated on an integer scale from 1-4). Analysis was performed on the surgeon-specific outcome measures for the overall operation, and for each defined step. Normality of data distribution is not

assumed, and non-parametric statistical tests are used. The Kruskal-Wallis test was used to determine any significant differences in outcome metrics measured using continuous data (time, movement counts, MLA, OHS, EQ-5D VAS, RI, RA, RLLD, RFSA, OTBL, Hb, and length of stay) for the factors with more than two categories (PGY, total number of primary THR performed as first surgeon category, and PBA level). The Mann-Whitney test was used to determine any significant differences in outcome metrics measured using continuous data for factors with two categories (surgeon group). The Pearson's Chi-squared (χ^2) or Fishers exact test was used to determine any significant differences in categorical outcome metrics (EQ-5D questions 1-5, incidence of transfusion, femoral cementation grade, and re-operation/re-admission). Following a significant Kruskal-Wallis test, Dunn's test of multiple comparisons is used to determine any pairwise significant differences between groups. Mean and standard deviations were used for descriptive statistics. ASA and BMI data are presented as outlined in study A (8.2.2). Missing or omitted data are not included in the statistical analysis but are recorded in data tables as 'unknown'. Data analysis and visualisation was performed using RStudio (RStudio Team (2021): Integrated Development for R. RStudio, PBC, Boston, MA). The significance threshold was set at 0.05 for all statistical analysis, and data visualisation is presented for significant findings.

8.3.3 Results

A total of seven StRs and 52 patient participants were recruited into this study. Most StRs were male (n=6, or 85.7%), and right-handed (n=6, or 85.7%). The only female StR, and the left-handed male StR were both in the intervention group. Within these surgeon participants, four had previously been randomised into the intervention group, and three into the control group. Surgeon participants within the intervention group performed a total of 25 THRs, and participants within the control group performed a total of 27 THRs. The number of THR recorded for each StR ranged from three to 12 (median=7, mean=7.4). Within the 52 patient participants, 37 (71.5%) were recruited from the Nuffield Orthopaedic Centre, and 15 (28.5%) from Wycombe General Hospital. Overall, 48 (92.3%) consented for use of their personal medical data, including electronic patient records (EPR) radiographs, and blood results.

Table 8-12: The number of patient recordings performed, group allocation, and training profile of StR participants.

** StR participant ID **	**Overall**, N = 52[1]	**R1**, N = 3[1]	**R2**, N = 10[1]	**R3**, N = 7[1]	**R4**, N = 12[1]	**R5**, N = 5[1]	**R6**, N = 11[1]	**R7**, N = 4[1]
StR Group								
Simulation training	25	3	10	7	0	5	0	0
Control	27	0	0	0	12	0	11	4
PGY category								
1/2	9	0	0	0	0	5	0	4
3/4	30	0	0	7	12	0	11	0
5/6	13	3	10	0	0	0	0	0
THR performed as first surgeon								
0-19	16	0	0	7	0	5	0	4
20-39	23	0	0	0	12	0	11	0
>40	13	3	10	0	0	0	0	0
PBA level								
2	6	0	0	0	0	5	0	1
3	17	0	0	3	11	0	2	1
4	19	0	9	1	1	0	8	0
Unknown	10	3	1	3	0	0	1	2

[1] n

8.3.3.1 Implant fixation

Hybrid implant fixation was the most common, representing 69.2% (n=36) of all cases. This was followed by all uncemented implants, representing 17.3% of cases (n=9), and all cemented implants being the least common with 13.5% of cases (n=7). There was no significant difference in implant fixation in relation to StR group (p=0.6).

Table 8-13: Implant fixation in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Implant Fixation				0.6
Hybrid	36 (69.2%)	19 (76.0%)	17 (63.0%)	
Uncemented	9 (17.3%)	3 (12.0%)	6 (22.2%)	
Cemented	7 (13.5%)	3 (12.0%)	4 (14.8%)	

[1] n (%)

[2] Fisher's exact test

8.3.3.2 Patient demographics

Most patients were female (84.6%, n=44). The mean patient age was 70.2 years old (SD 10.8). The mean patient body mass index (BMI) was 28.3kg/m^2, and most were in the overweight category (48%, n=25). The median patient ASA grade was 2 (75%, n=36). No significant differences were observed in patient gender (p>0.9), age (p=0.8), age category (p=0.3), BMI (p=0.6), BMI category (p=0.5), ASA (p=0.6), or ASA category (p=0.4) according to StR group.

Table 8-14: Patient demographics in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Gender				
				>0.9
Female	44 (84.6%)	21 (84.0%)	23 (85.2%)	
Male	8 (15.4%)	4 (16.0%)	4 (14.8%)	
Age				
Age	70.2 (10.8)	70.3 (11.0)	70.1 (10.8)	0.8
Age Category				0.3
41-60	13 (25%)	7 (28%)	6 (22%)	
61-80	30 (58%)	12 (48%)	18 (67%)	
81-100	9 (17%)	6 (24%)	3 (11%)	
BMI				
Body Mass Index	28.3 (5.4)	27.8 (4.7)	28.7 (6.1)	0.6
BMI Category				0.5
Normal	11 (21%)	5 (20%)	6 (22%)	
Overweight	25 (48%)	14 (56%)	11 (41%)	
Obese	16 (31%)	6 (24%)	10 (37%)	
ASA				
ASA				0.6
2	36 (75.0%)	17 (81.0%)	19 (70.4%)	
3	10 (20.8%)	4 (19.0%)	6 (22.2%)	
4	2 (4.2%)	0 (0.0%)	2 (7.4%)	
Unknown	4	4	0	
ASA Category				0.4
1/2	36 (75.0%)	17 (81.0%)	19 (70.4%)	
3/4	12 (25.0%)	4 (19.0%)	8 (29.6%)	
Unknown	4	4	0	

[1] n (%)
[2] Fisher's exact test

8.3.3.3 Surgeon-specific metrics

1) Operative time

Overall

The mean operative time to perform a primary elective THR across all StRs was 4678 seconds, or 1hour 17minutes 58seconds. No significant difference was observed in operative times according to StR group (p=0.12). Significant differences were observed in the mean operative time in relation to PGY (p=0.0042), STS-THR (p=0.00029), and PBA level (p=0.00018). PGY 1/2 were observed to have significantly slower mean operating times (6029 seconds, or 1hour 40minute 29seconds) in comparison to PGY 3/4 (4437 seconds, or 1hour 13minutes 57seconds, p=0.0023) and PGY 5/6 (4429 seconds, or 1hour 11minutes 39seconds, p=0.0027). StRs with STS-THR 0-19 were observed to have significantly slower mean operating times (5693 seconds, or 1hour 34minute 53seconds) in comparison to STS-THR 20-39 (4187 seconds, or 1hour 9minutes 47seconds, p=0.00013) and STS-THR >40 (4299 seconds, or 1hour 11minutes 39seconds, p=0.0022). StRs rated as PBA level 2 were observed to have significantly slower mean operating times (6264 seconds, or 1hour 44minute 24seconds) in comparison to those rated as PBA level 4 (3893 seconds, or 1hour 4minutes 53seconds, p=0.0054), but not PBA level 3 (4799 seconds, or 1hour 19minutes 59seconds, p=0.066). StRs rated as PBA level 3 were observed to have significantly slower mean operating times than those rated as PBA level 4 (p=0.0055).

Steps

Significant differences were observed in the mean operative time in relation to StR group for the femoral cementing step only, where StRs from the intervention group demonstrated significantly slower mean times in comparison to the control group. Significant differences were observed in relation to PGY and STS-THR for 4 out of the 16 steps, namely the surgical approach; acetabular reaming; femoral broaching; and initial head trialling steps (all $p<0.05$, see tables 8-16 and 8-17). Significant differences were observed in relation to PBA level for 3 out of the 16 steps, namely the surgical approach; acetabular reaming; and femoral broaching steps (all $p<0.05$, see table 8-18).

Surgical approach

PGY 1/2 demonstrated significantly slower mean times in comparison to PGY 3/4 and PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly slower mean times in comparison to STS-THR 20-39 and >40. StRs rated as PBA level 2 demonstrated significantly slower mean times in comparison to those rated as PBA level 3 and 4. StRs rated as PBA level 3 also demonstrated significantly slower mean times than those rated as PBA level 4.

Acetabular reaming

PGY 1/2 demonstrated significantly slower mean times in comparison to PGY 3/4 and 5/6. StRs with STS-THR 0-19 demonstrated significantly slower mean times in comparison to STS-THR 20-39 and >40. StRs rated as PBA level 2 demonstrated significantly slower mean times in comparison to those rated as PBA level 4, but not level 3. StRs rated as PBA level 3 demonstrated significantly slower mean times than those rated as PBA level 4.

Femoral broaching

PGY 1/2 demonstrated significantly slower mean times in comparison to PGY 5/6, but not 3/4. PGY 3/4 demonstrated significantly slower mean times than PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly slower mean times in comparison to STS-THR 20-39 and >40. StRs rated as PBA level 2 demonstrated significantly slower mean times in comparison to those rated as PBA level 4, but not level 3. StRs rated as PBA level 3 demonstrated significantly slower mean times than those rated as PBA level 4.

Initial head trialling

PGY 1/2 demonstrated significantly slower mean times in comparison to PGY 3/4, but not 5/6. StRs with STS-THR 0-19 demonstrated significantly slower mean times in comparison to STS-THR 20-39, but not >40. StRs with STS-THR 20-39 demonstrated significantly faster mean times than those with STS-THR >40.

Table 8-15: Operative time in relation to StR group.

	Overall, N = 52[1]	Simulation training, N = 25[1]	Control, N = 27[1]	p-value[2]
Total time				
Total Time	4,678 (1,140)	4,948 (1,119)	4,428 (1,122)	0.12
Step time				
Approach	617 (224)	669 (196)	569 (240)	0.10
Hip dislocation	81 (49)	87 (62)	75 (34)	0.9
Unknown	1	1	0	
Femoral neck osteotomy	91 (61)	93 (43)	90 (75)	0.2
Acetabular exposure	293 (134)	284 (118)	301 (149)	0.9
Acetabular reaming	271 (154)	309 (191)	236 (100)	0.2
Acetabular implantation	433 (254)	470 (302)	399 (198)	0.8
Femoral broaching	332 (110)	346 (132)	320 (84)	0.6
Initial trial	219 (162)	264 (188)	184 (133)	0.079
Unknown	4	4	0	
Femoral cement preparation	222 (127)	231 (172)	213 (51)	0.4
Unknown	9	3	6	
Femoral cementing	118 (26)	127 (30)	109 (16)	**0.023**
Unknown	9	3	6	
Femoral stem insertion	385 (152)	404 (121)	366 (177)	0.4
Definitive trial	197 (86)	199 (103)	195 (70)	0.8
Unknown	3	2	1	
Closure	1,224 (279)	1,283 (248)	1,168 (299)	0.3

[1] Mean (SD)

[2] Wilcoxon rank sum test

Figure 8-9: Operative time in relation to StR group.

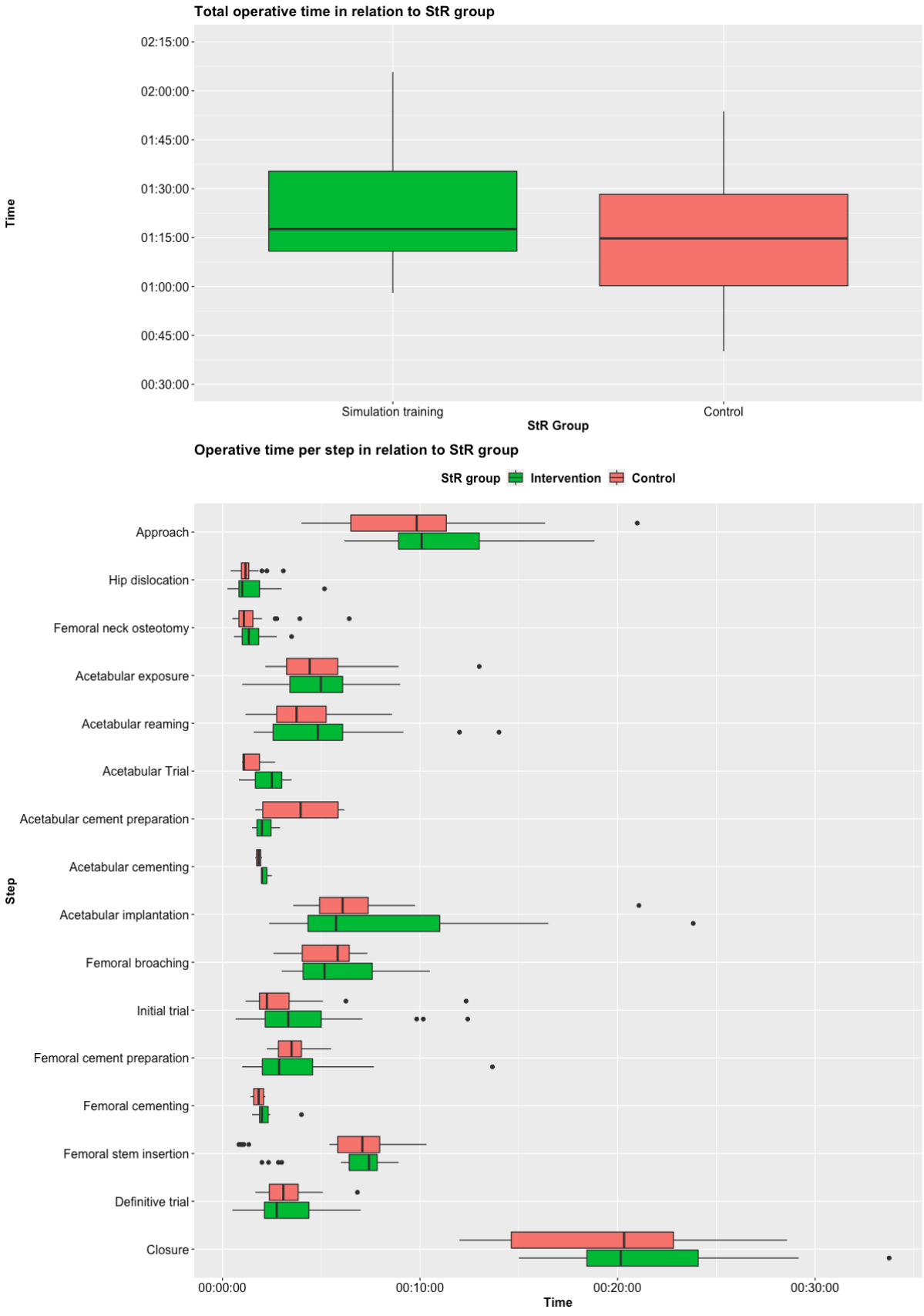


Table 8-16: Operative time in relation to StR PGY.

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Total time					
Total Time (seconds)	4,678 (1,140)	6,029 (1,201)	4,437 (1,030)	4,299 (574)	**0.004**
Step time					
Approach	617 (224)	946 (202)	533 (166)	583 (138)	**<0.001**
Hip dislocation	81 (49)	101 (83)	72 (35)	87 (44)	0.5
Unknown	1	0	1	0	
Femoral neck osteotomy	91 (61)	97 (43)	96 (74)	76 (33)	0.5
Acetabular exposure	293 (134)	409 (181)	270 (97)	265 (140)	0.065
Acetabular reaming	271 (154)	417 (183)	245 (87)	231 (202)	**0.005**
Acetabular implantation	433 (254)	487 (243)	461 (286)	331 (144)	0.2
Femoral broaching	332 (110)	416 (98)	336 (106)	266 (88)	**0.007**
Initial trial	219 (162)	316 (223)	174 (109)	271 (203)	**0.047**
Unknown	4	0	0	4	
Femoral cement preparation	222 (127)	306 (218)	209 (83)	177 (78)	0.2
Unknown	9	0	6	3	
Femoral cementing	118 (26)	111 (15)	115 (20)	132 (40)	0.4
Unknown	9	0	6	3	
Femoral stem insertion	385 (152)	424 (58)	382 (172)	363 (154)	>0.9
Definitive trial	197 (86)	196 (51)	206 (83)	174 (115)	0.2
Unknown	3	0	1	2	
Closure	1,224 (279)	1,422 (331)	1,182 (290)	1,181 (140)	0.13

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-10: Operative time in relation to StR PGY.

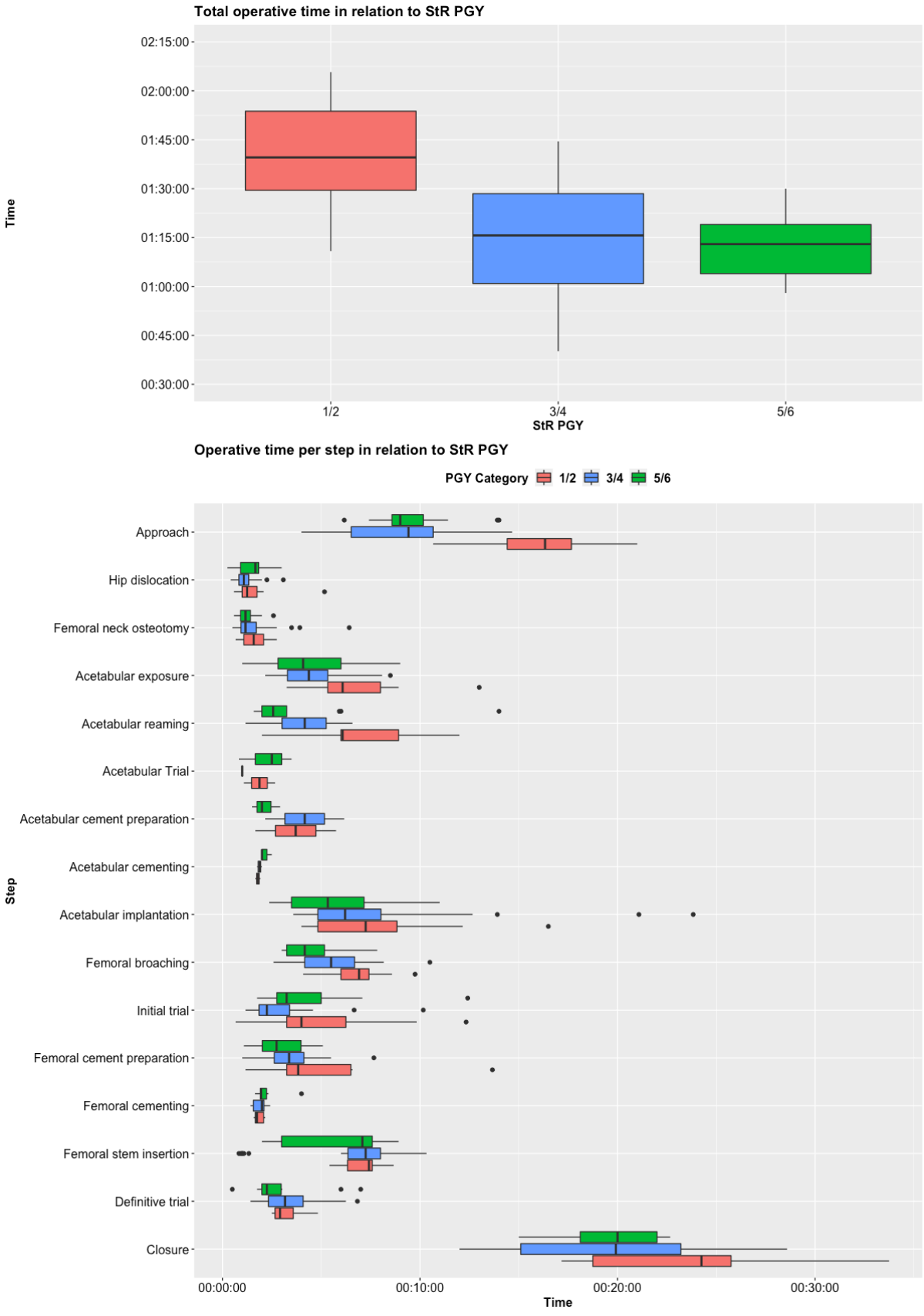


Table 8-17: Operative time in relation to the total number of supervised THR performed with StR as first surgeon.

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Total time					
Total Time (seconds)	4,678 (1,140)	5,693 (1,107)	4,187 (955)	4,299 (574)	**<0.001**
Step time					
Approach	617 (224)	806 (229)	505 (173)	583 (138)	**<0.001**
Hip dislocation	81 (49)	85 (68)	74 (36)	87 (44)	0.7
Unknown	1	1	0	0	
Femoral neck osteotomy	91 (61)	98 (46)	94 (80)	76 (33)	0.3
Acetabular exposure	293 (134)	361 (153)	261 (101)	265 (140)	0.059
Acetabular reaming	271 (154)	372 (150)	224 (82)	231 (202)	**0.001**
Acetabular implantation	433 (254)	564 (327)	399 (212)	331 (144)	0.056
Femoral broaching	332 (110)	422 (105)	308 (84)	266 (88)	**<0.001**
Initial trial	219 (162)	295 (201)	145 (53)	271 (203)	**0.011**
Unknown	4	0	0	4	
Femoral cement preparation	222 (127)	261 (188)	211 (55)	177 (78)	0.4
Unknown	9	0	6	3	
Femoral cementing	118 (26)	119 (19)	109 (16)	132 (40)	0.10
Unknown	9	0	6	3	
Femoral stem insertion	385 (152)	432 (55)	364 (191)	363 (154)	0.9
Definitive trial	197 (86)	218 (79)	192 (74)	174 (115)	0.12
Unknown	3	0	1	2	
Closure	1,224 (279)	1,352 (282)	1,158 (313)	1,181 (140)	0.12

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-11: Operative time in relation to the total number of supervised THR performed with StR as first surgeon.

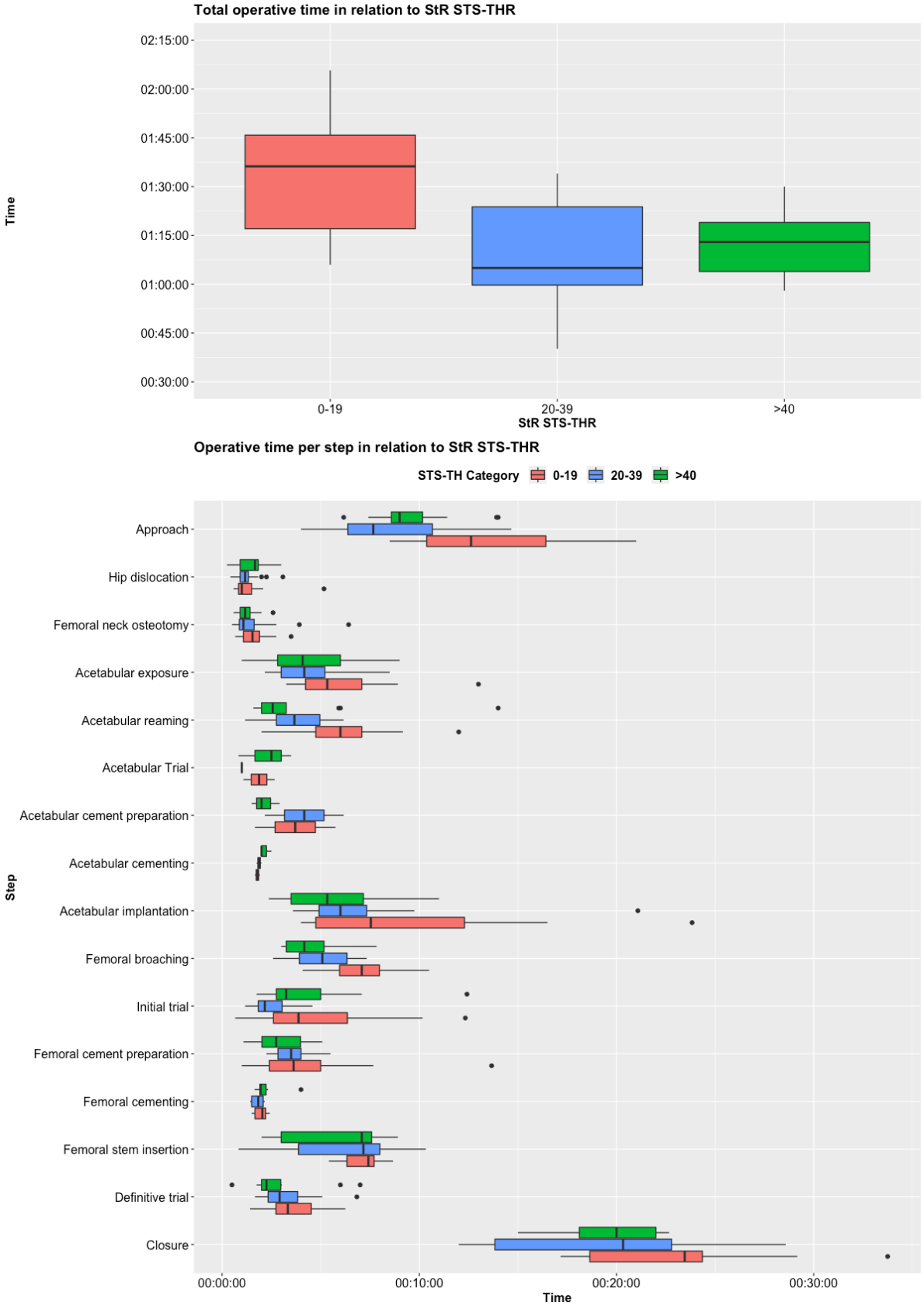


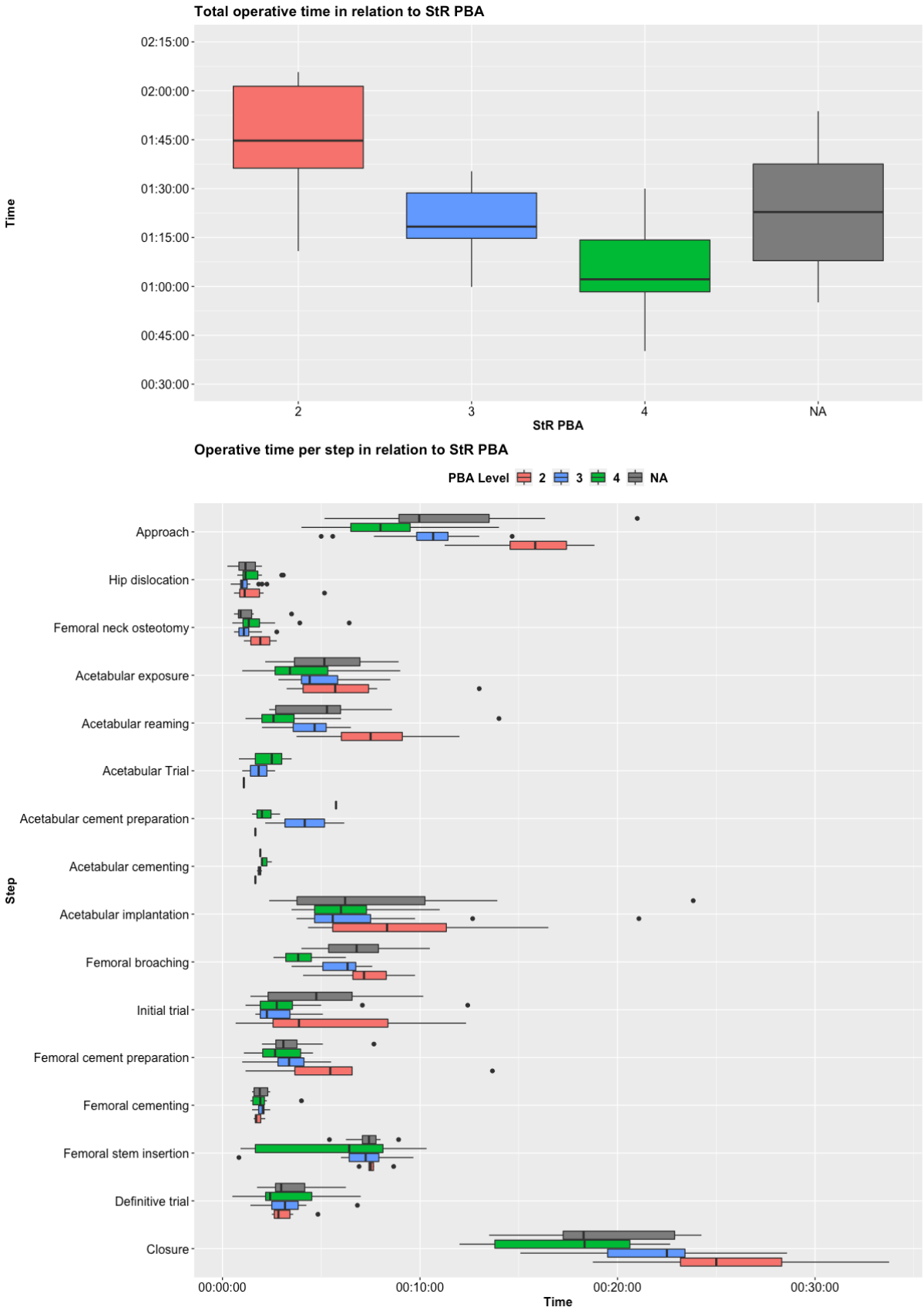
Table 8-18: Operative time in relation to StR PBA level.

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Total time					
Total Time (seconds)	4,599 (1,131)	6,264 (1,246)	4,799 (664)	3,893 (777)	**<0.001**
Step time					
Approach	601 (209)	938 (162)	609 (147)	488 (148)	**<0.001**
Hip dislocation	83 (51)	109 (103)	68 (31)	88 (41)	0.4
Femoral neck osteotomy	95 (63)	115 (39)	73 (33)	107 (83)	0.058
Acetabular exposure	286 (135)	392 (215)	302 (98)	239 (117)	0.071
Acetabular reaming	267 (161)	459 (176)	265 (73)	208 (171)	**<0.001**
Acetabular implantation	418 (211)	545 (277)	427 (257)	370 (116)	0.3
Femoral broaching	315 (102)	432 (116)	355 (67)	241 (62)	**<0.001**
Initial trial	208 (156)	328 (275)	166 (63)	207 (156)	0.5
Femoral cement preparation	223 (136)	358 (257)	206 (68)	175 (72)	0.12
Unknown	9	0	1	8	
Femoral cementing	119 (27)	108 (14)	121 (14)	122 (43)	0.3
Unknown	9	0	1	8	
Femoral stem insertion	372 (165)	457 (35)	421 (112)	300 (201)	0.2
Definitive trial	193 (86)	192 (53)	193 (79)	194 (106)	0.8
Unknown	3	0	0	3	
Closure	1,238 (292)	1,545 (312)	1,332 (217)	1,058 (226)	**<0.001**

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-12: Operative time in relation to StR PBA level.



2) Movement count

Overall

The mean total movement count (combined right and left hands) to perform a primary elective THR across all StRs was 172,115. No significant differences were observed in the mean total movement count according to StR group (p=0.8), or STS-THR (p=0.083). Significant differences were observed in the mean total movement count in relation to PGY (p=0.008), and PBA level (p=8.43e-05). PGY 1/2 were observed to have significantly greater mean total movement count in comparison to PGY 3/4 (p=0.0067) and PGY 5/6 (p=0.0029). StRs rated as PBA level 2 were observed to have significantly greater mean total movement count in comparison to those rated as PBA level 4 (p=0.00018), but not PBA level 3 (p=0.17). StRs rated as PBA level 3 were observed to have significantly greater mean total movement count than those rated as PBA level 4 (p=0.00096).

Steps

No significant differences were observed in the mean total movement count in relation to StR group. Significant differences were observed in relation to PGY for 3 out of the 16 steps, namely the surgical approach; acetabular reaming; and femoral broaching. (All $p<0.05$, see table 8-20). Significant differences were observed in relation to STS-THR for 4 out of the 16 steps, namely the surgical approach; acetabular reaming; femoral broaching; and initial head trialling (All $p<0.05$, see table 8-21). Significant differences were observed in relation to PBA level for 5 out of the 16 steps, namely the surgical approach; acetabular reaming; femoral broaching; femoral cementing; and closure (All $p<0.05$, see table 8-22).

Surgical approach

PGY 1/2 demonstrated significantly greater mean total movement count in comparison to PGY 3/4 and 5/6. StRs with STS-THR 0-19 demonstrated significantly greater mean total movement count in comparison to STS-THR 20-39 and >40. StRs rated as PBA level 2 demonstrated significantly greater mean total movement count in comparison to those rated as PBA level 3 and 4. StRs rated as PBA level 3 demonstrated significantly greater mean total movement count than those rated as PBA level 4.

Acetabular reaming

PGY 1/2 demonstrated significantly greater mean total movement count in comparison to PGY 5/6, but not 3/4. PGY 3/4 also demonstrated significantly greater mean total movement count in comparison to PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly greater mean total movement count in comparison to STS-THR 20-39 and >40. StRs rated PBA level 2 demonstrated significantly greater mean total movement count in comparison to those rated PBA level 4, but not level 3. StRs rated PBA level 3 demonstrated significantly greater mean total movement count than those rated level 4.

Femoral broaching

PGY 1/2 demonstrated significantly greater mean total movement count in comparison to PGY 5/6, but not 3/4. PGY 3/4 demonstrated significantly greater mean total movement count than PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly greater mean total movement count in comparison to STS-THR 20-39 and >40. StRs rated PBA level 2 demonstrated significantly greater mean total movement count in comparison to those rated level 4, but not level 3. StRs rated PBA level 3 demonstrated significantly greater mean total movement count than those rated level 4.

Initial head trialling

StRs with STS-THR 0-19 demonstrated significantly greater mean total movement count in comparison to STS-THR 20-39, but not >40.

Femoral canal cementing

StRs rated PBA level 2 demonstrated significantly fewer mean average movement counts in comparison to those rated level 3, but not level 4. StRs rated PBA level 3 demonstrated significantly greater mean average movement counts than those rated as PBA level 4.

Surgical closure

StRs rated PBA level 2 demonstrated significantly greater mean average movement counts in comparison to those rated as PBA level 4, but not level 3. StRs rated PBA level 3 demonstrated significantly greater mean average movement counts than those rated PBA level 4.

Table 8-19: Total movement count in relation to StR group.

	Overall, N = 52[1]	Simulation training, N = 25[1]	Control, N = 27[1]	p-value[2]
Total movement counts				
Total movement count	172,115 (42,176)	171,967 (41,867)	172,258 (43,300)	0.8
Unknown	1	0	1	
Step movement counts				
Approach	25,343 (9,028)	27,018 (7,822)	23,792 (9,911)	0.2
Hip dislocation	3,376 (1,917)	3,509 (2,385)	3,253 (1,393)	0.8
Unknown	2	1	1	
Femoral neck osteotomy	3,484 (1,891)	3,711 (1,803)	3,266 (1,983)	0.2
Unknown	1	0	1	
Acetabular exposure	11,917 (5,682)	11,491 (4,880)	12,327 (6,430)	0.8
Unknown	1	0	1	
Acetabular reaming	11,154 (5,807)	11,845 (7,117)	10,540 (4,382)	0.8
Unknown	1	1	0	
Acetabular implantation	16,383 (8,838)	16,203 (9,207)	16,537 (8,685)	0.5
Unknown	2	2	0	
Femoral broaching	13,100 (4,416)	13,261 (5,273)	12,956 (3,587)	>0.9
Unknown	1	1	0	
Initial trial	8,011 (5,892)	9,420 (6,722)	6,926 (5,034)	0.12
Unknown	6	5	1	
Femoral cement preparation	8,609 (4,839)	8,457 (6,521)	8,769 (2,119)	0.2
Unknown	11	4	7	
Femoral cementing	5,153 (1,102)	5,264 (1,298)	5,036 (870)	0.8
Unknown	11	4	7	
Femoral stem insertion	15,617 (6,503)	15,827 (5,113)	15,423 (7,665)	0.5
Unknown	2	1	1	
Definitive trial	7,545 (3,404)	7,393 (4,033)	7,679 (2,817)	0.4
Unknown	5	3	2	
Closure	49,580 (10,989)	50,881 (9,282)	48,519 (12,278)	0.7
Unknown	3	3	0	

[1] Mean (SD)

[2] Wilcoxon rank sum test

Figure 8-13: Total movement count in relation to StR group.

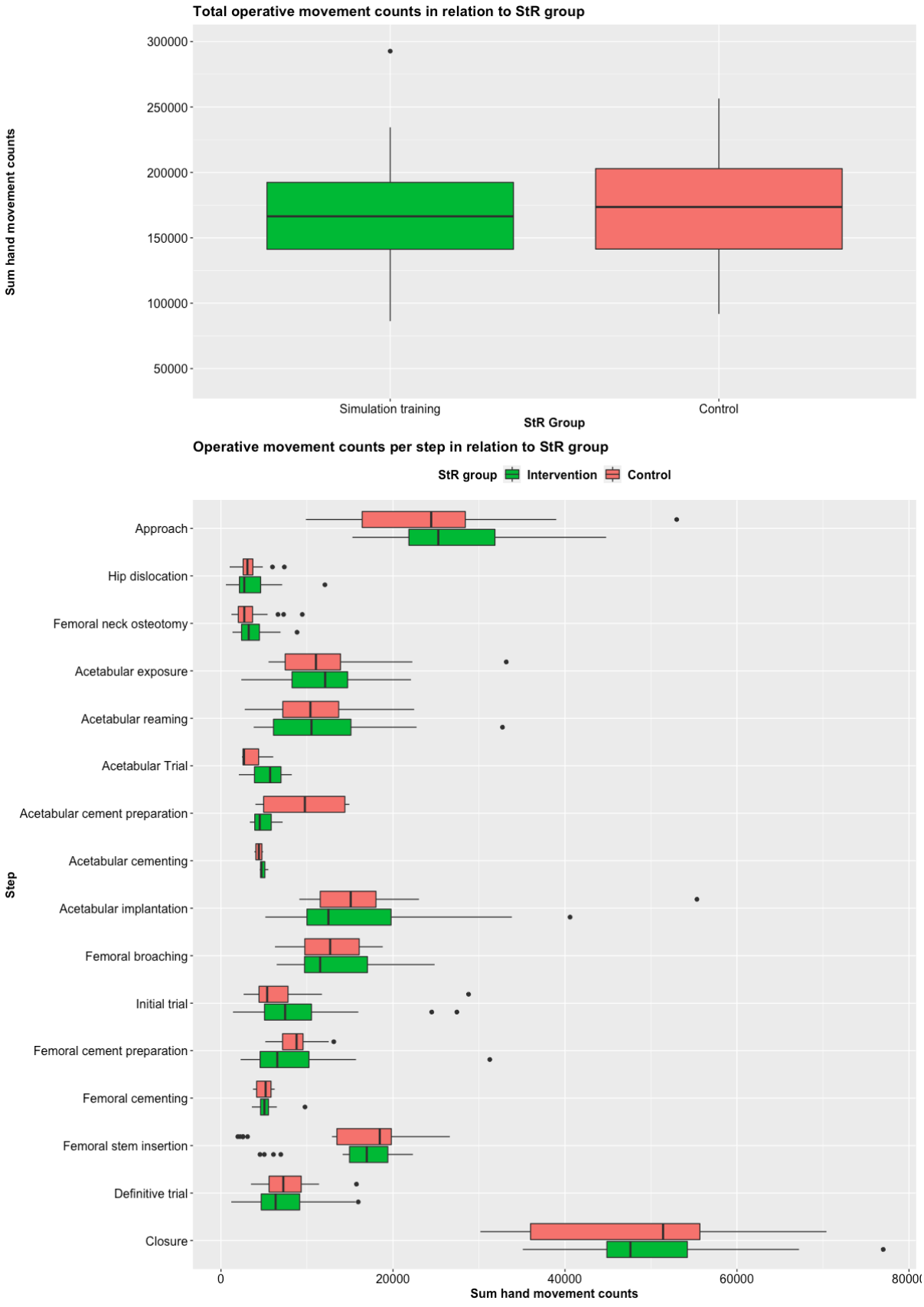


Table 8-20: Total movement count in relation to StR PGY.

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Total movement counts					
Total movement counts	172,115 (42,176)	217,448 (43,385)	165,924 (41,301)	158,506 (22,914)	**0.008**
Unknown	1	1	0	0	
Step movement counts					
Approach	25,343 (9,028)	38,101 (8,713)	22,340 (6,854)	23,442 (5,810)	**<0.001**
Hip dislocation	3,376 (1,917)	4,138 (3,419)	3,123 (1,387)	3,471 (1,774)	0.8
Unknown	2	1	1	0	
Femoral neck osteotomy	3,484 (1,891)	4,153 (1,759)	3,521 (2,121)	2,990 (1,289)	0.3
Unknown	1	1	0	0	
Acetabular exposure	11,917 (5,682)	16,477 (8,325)	11,270 (4,280)	10,603 (5,747)	0.14
Unknown	1	1	0	0	
Acetabular reaming	11,154 (5,807)	16,027 (6,329)	10,894 (3,845)	8,755 (7,692)	**0.004**
Unknown	1	1	0	0	
Acetabular implantation	16,383 (8,838)	19,295 (9,983)	17,212 (9,371)	12,584 (5,597)	0.10
Unknown	2	0	2	0	
Femoral broaching	13,100 (4,416)	16,301 (3,746)	13,398 (4,270)	10,218 (3,533)	**0.005**
Unknown	1	0	1	0	
Initial trial	8,011 (5,892)	12,101 (9,558)	6,238 (2,743)	10,086 (7,486)	0.081
Unknown	6	1	1	4	
Femoral cement preparation	8,609 (4,839)	12,379 (8,766)	8,122 (2,646)	6,714 (3,157)	0.12
Unknown	11	1	7	3	
Femoral cementing	5,153 (1,102)	4,613 (711)	5,192 (923)	5,495 (1,590)	0.3
Unknown	11	1	7	3	
Femoral stem insertion	15,617 (6,503)	16,952 (2,197)	15,960 (7,403)	14,029 (6,146)	0.3
Unknown	2	1	1	0	
Definitive trial	7,545 (3,404)	7,683 (2,033)	7,938 (3,343)	6,445 (4,296)	0.2
Unknown	5	1	2	2	
Closure	49,580 (10,989)	55,588 (12,615)	49,032 (12,072)	47,063 (5,536)	0.2
Unknown	3	1	2	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-14: Total movement count in relation to StR PGY.

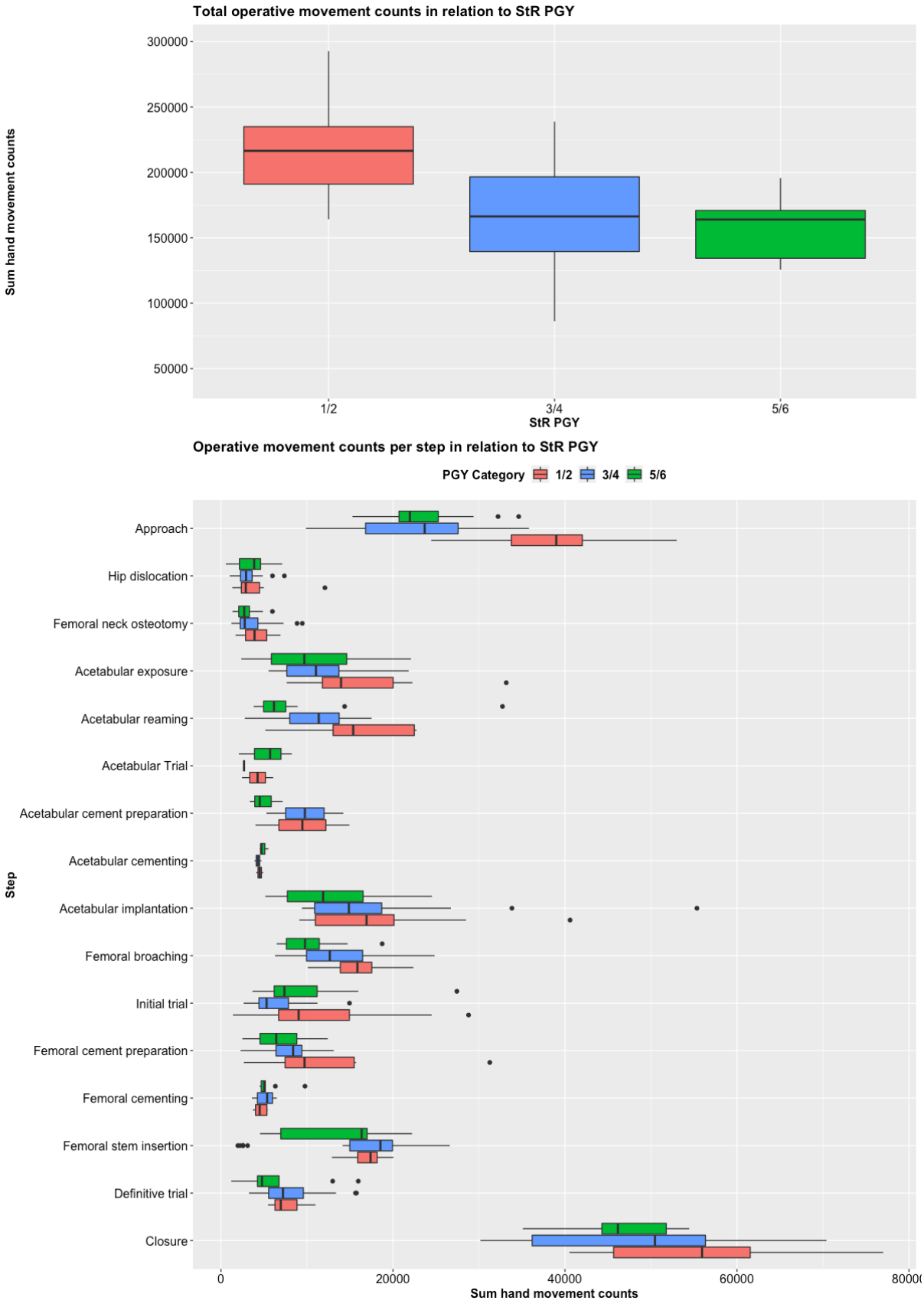


Table 8-21: Total movement count in relation to the total number of supervised THR performed with StR as first surgeon.

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Total movement counts					
Total movement count	172,115 (42,176)	192,590 (51,640)	166,455 (40,382)	158,506 (22,914)	0.083
Unknown	1	1	0	0	
Step movement counts					
Approach	25,343 (9,028)	32,691 (9,259)	21,306 (7,325)	23,442 (5,810)	**0.001**
Hip dislocation	3,376 (1,917)	3,514 (2,696)	3,238 (1,462)	3,471 (1,774)	0.8
Unknown	2	2	0	0	
Femoral neck osteotomy	3,484 (1,891)	4,157 (1,952)	3,325 (2,078)	2,990 (1,289)	0.13
Unknown	1	1	0	0	
Acetabular exposure	11,917 (5,682)	14,537 (6,625)	10,951 (4,554)	10,603 (5,747)	0.10
Unknown	1	1	0	0	
Acetabular reaming	11,154 (5,807)	14,967 (5,055)	10,024 (3,668)	8,755 (7,692)	**<0.001**
Unknown	1	1	0	0	
Acetabular implantation	16,383 (8,838)	19,436 (9,762)	16,673 (9,275)	12,584 (5,597)	0.092
Unknown	2	2	0	0	
Femoral broaching	13,100 (4,416)	16,411 (4,191)	12,569 (3,697)	10,218 (3,533)	**0.001**
Unknown	1	1	0	0	
Initial trial	8,011 (5,892)	10,388 (7,737)	5,752 (2,136)	10,086 (7,486)	**0.044**
Unknown	6	2	0	4	
Femoral cement preparation	8,609 (4,839)	9,771 (7,401)	8,767 (2,233)	6,714 (3,157)	0.2
Unknown	11	2	6	3	
Femoral cementing	5,153 (1,102)	5,008 (957)	5,071 (879)	5,495 (1,590)	>0.9
Unknown	11	2	6	3	
Femoral stem insertion	15,617 (6,503)	17,404 (2,558)	15,427 (8,134)	14,029 (6,146)	0.3
Unknown	2	2	0	0	
Definitive trial	7,545 (3,404)	8,406 (3,309)	7,547 (2,947)	6,445 (4,296)	0.2
Unknown	5	2	1	2	
Closure	49,580 (10,989)	54,177 (10,821)	48,404 (12,853)	47,063 (5,536)	0.2
Unknown	3	3	0	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-15: Total movement count in relation to the total number of supervised THR performed with StR as first surgeon.

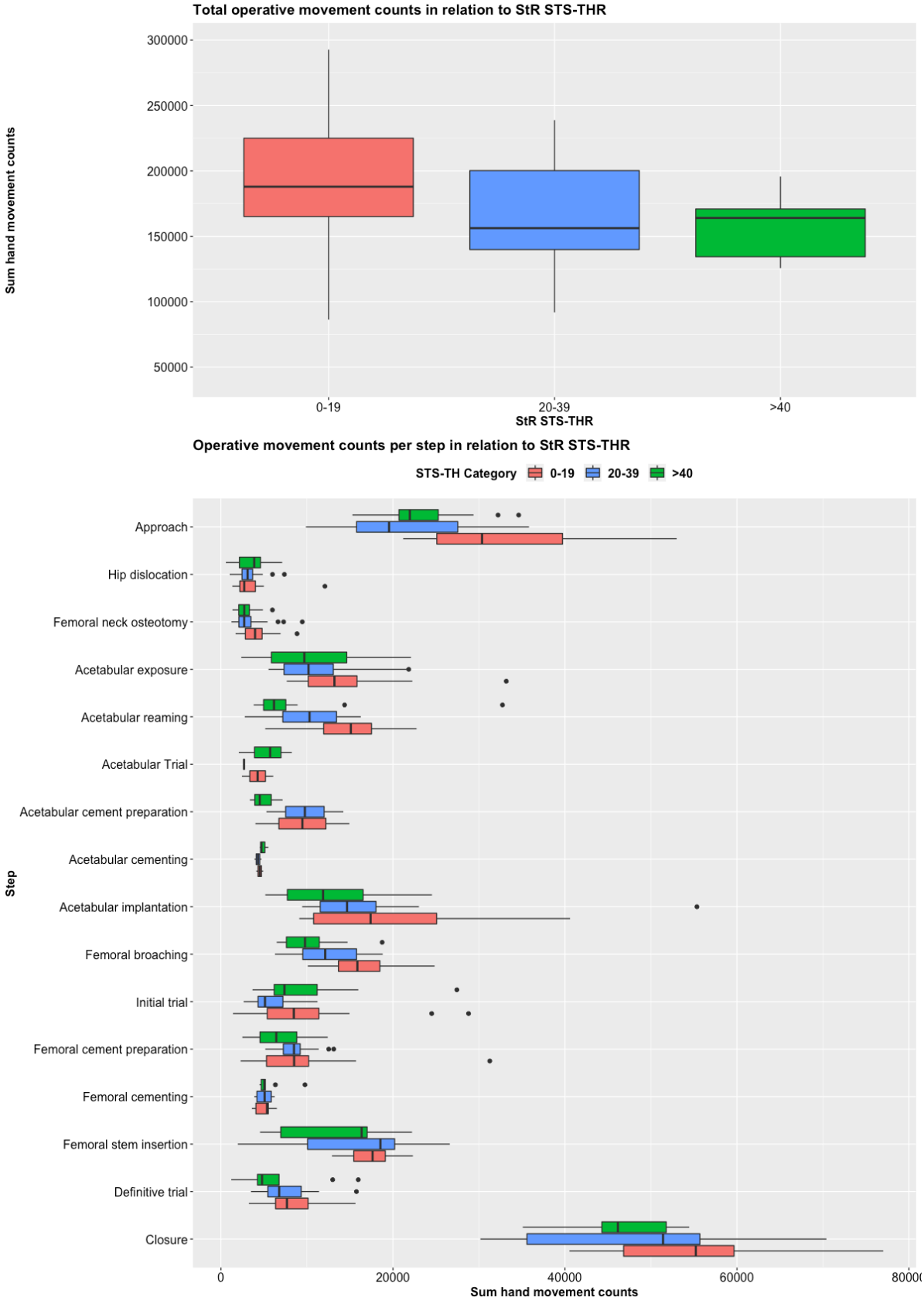


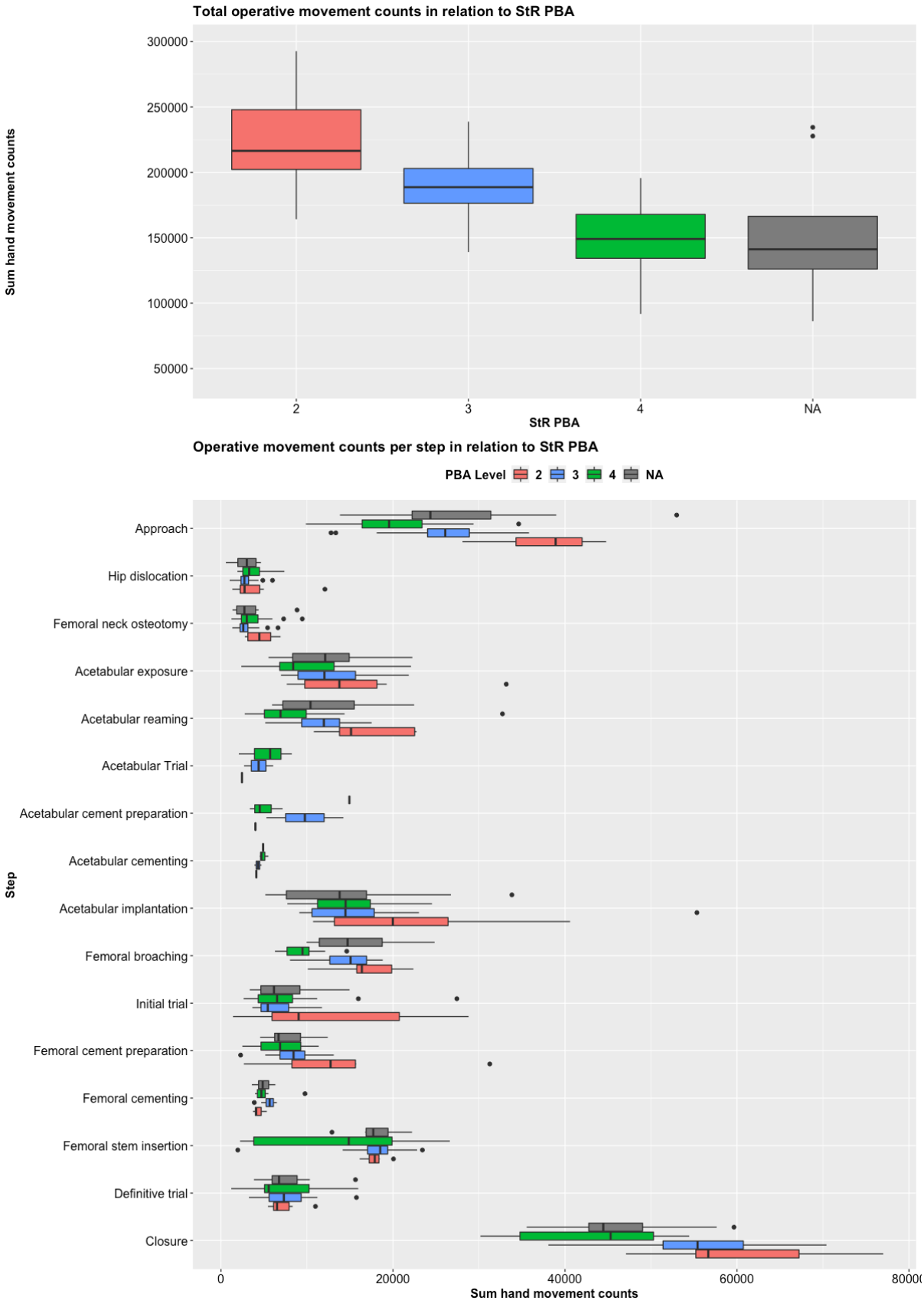
Table 8-22: Total movement count in relation to StR PBA level.

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Total movement counts					
Total movement count	175,481 (40,559)	224,306 (45,022)	188,247 (26,565)	148,640 (29,116)	**<0.001**
Step movement counts					
Approach	24,768 (8,421)	37,748 (6,286)	25,340 (6,146)	20,157 (6,170)	**<0.001**
Hip dislocation	3,468 (1,990)	4,344 (3,989)	2,917 (1,306)	3,685 (1,579)	0.3
Femoral neck osteotomy	3,514 (1,818)	4,592 (1,701)	3,018 (1,400)	3,617 (2,086)	0.11
Acetabular exposure	11,870 (5,795)	16,061 (9,380)	12,632 (4,531)	9,866 (4,812)	0.085
Acetabular reaming	10,991 (5,903)	16,994 (5,380)	11,784 (3,320)	8,701 (6,713)	**0.002**
Unknown	1	1	0	0	
Acetabular implantation	16,579 (8,790)	21,791 (11,355)	16,764 (11,088)	14,777 (4,576)	0.3
Unknown	1	0	1	0	
Femoral broaching	12,533 (4,170)	16,974 (4,337)	14,555 (3,022)	9,321 (2,223)	**<0.001**
Initial trial	8,044 (6,014)	12,968 (11,058)	6,503 (2,465)	7,868 (5,716)	0.5
Femoral cement preparation	8,838 (5,256)	13,795 (9,867)	8,352 (2,756)	6,841 (2,970)	0.14
Unknown	9	0	1	8	
Femoral cementing	5,204 (1,147)	4,350 (613)	5,576 (695)	5,129 (1,623)	**0.005**
Unknown	9	0	1	8	
Femoral stem insertion	15,181 (6,932)	17,916 (1,330)	17,512 (4,701)	12,231 (8,515)	0.3
Definitive trial	7,482 (3,383)	7,312 (2,044)	7,612 (3,202)	7,408 (4,077)	0.8
Unknown	3	0	0	3	
Closure	50,183 (11,440)	60,639 (11,616)	55,317 (9,209)	42,837 (8,559)	**<0.001**
Unknown	1	1	0	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-16: Total movement count in relation to StR PBA level.



3) Magnitude of linear acceleration (MLA)

Overall

The mean right- and left- hand MLA when performing a primary elective THR across all StRs were 0.0008 and 0.0005m/s^2, respectively. Significant differences were observed in the mean right-hand MLA according to the StR group (p=0.01), PGY (p=0.016), STS-THR (p=0.007), but not PBA level (p=0.13). No significant differences were observed in the mean left-hand MLA according to the StR group (p=0.9), PGY (p=0.2), STS-THR (p=0.8), or PBA level (p=0.086).

Steps

Significant differences were observed in the mean right-hand MLA in relation to the StR group for 4 out of the 16 steps, namely the acetabular exposure; acetabular reaming; and femoral cement preparation; and closure (All p<0.05, see table 8-23). Significant differences were also observed in the mean left-hand MLA in relation to the StR group for a single step, namely femoral broaching. Significant differences were observed in the mean right-hand MLA in relation to the PGY for 6 out of the 16 steps, namely the acetabular exposure; acetabular reaming; femoral broaching; initial trial; femoral cement preparation; femoral cementing; and closure (All p<0.05, see table 8-24). Significant differences were also observed in the mean left-hand MLA in relation to the PGY for 6 out of the 16 steps, namely the acetabular exposure; acetabular reaming; acetabular cup implantation; femoral broaching; initial trial; and femoral cementing. Significant differences were observed in the mean right-hand MLA in relation to the STS-THR for 6 out of the 16 steps, namely the femoral neck osteotomy; acetabular exposure; acetabular reaming; femoral broaching; femoral cement preparation; and closure (All p<0.05, see table 8-25). Significant differences were also observed in the mean left-hand MLA in relation to the STS-THR for 3 out of the 16 steps, namely the femoral neck osteotomy; acetabular exposure; and acetabular reaming. Significant differences were observed in the mean right-hand MLA in relation to the PBA level for 7 out of the 16 steps, namely the acetabular exposure; acetabular reaming; acetabular cup implantation; femoral broaching; initial trial; femoral cement preparation; and femoral cementing (All p<0.05, see table 8-26). Significant differences were also observed in the mean left-hand MLA in relation to the PBA for 6 out of the 16

steps, namely hip dislocation; acetabular exposure; acetabular reaming; acetabular cup implantation; femoral cement preparation; and femoral cementing.

Hip dislocation

StRs rated as PBA level 3 demonstrated significantly greater mean total left-hand MLA in comparison to those rated as level 4, but not level 2. StRs rated PBA level 3 demonstrated significantly greater mean total left-hand MLA in comparison to those rated level 4.

Femoral neck osteotomy

StRs with STS-THR 0-19 demonstrated significantly lower mean total right- and left- hand MLA in comparison to STS-THR 20-39. StRs with STS-THR 0-19 were also observed to have significantly lower mean left- but not right-hand MLA in comparison to STS-THR >40.

Acetabular exposure

StRs from the intervention demonstrated significantly lower mean right-hand MLA in comparison to the control group. PGY 1/2 demonstrated significantly lower mean right- and left-hand MLA in comparison to PGY 3/4 and 5/6. StRs with STS-THR 0-19 demonstrated significantly lower mean total right- and left- hand MLA in comparison to STS-THR 20-39. StRs with STS-THR 0-19 demonstrated significantly lower mean left-hand MLA in comparison to STS-THR >40. StRs rated PBA level 2 demonstrated significantly lower mean total right- and left- hand MLA in comparison to PBA level 4. StRs rated PBA level 2 also demonstrated significantly lower mean left-hand MLA in comparison to those rated PBA level 3.

Acetabular reaming

StRs from the intervention group demonstrated significantly lower mean right-hand MLA in comparison to the control group. PGY 1/2 demonstrated significantly lower mean right- and left-hand MLA in comparison to PGY 3/4 and 5/6. StRs with STS-THR 0-19 demonstrated significantly lower mean total right- and left- hand MLA in comparison to STS-THR 20-39. StRs with STS-THR 0-19 also demonstrated significantly lower mean right- and left- hand MLA in comparison to STS-THR >40. StRs rated PBA level 2 demonstrated significantly lower mean total right- and left- hand

MLA in comparison to PBA level 3. StRs rated PBA level 2 also demonstrated significantly lower mean right- and left- hand MLA in comparison to those rated PBA level 4.

Acetabular cup implantation

PGY 1/2 demonstrated significantly lower mean left-hand MLA in comparison to PGY 3/4, but not PGY 5/6. StRs rated PBA level 2 demonstrated significantly lower mean total right- and left- hand MLA in comparison to PBA level 3.

Femoral broaching

StRs from the intervention group demonstrated significantly greater mean left-hand MLA in comparison to the control group. PGY 1/2 demonstrated significantly lower mean right- and left-hand MLA in comparison to PGY 5/6, and lower mean right-hand MLA in comparison to PGY 3/4. StRs with STS-THR 0-19 demonstrated significantly lower mean total right-hand MLA in comparison to STS-THR 20-39 and>40. StRs rated PBA level 2 demonstrated significantly lower mean total right-hand MLA in comparison to PBA level 4, but not level 3.

Initial head trialling

PGY 1/2 demonstrated significantly lower mean right- and left- hand MLA in comparison to PGY 3/4 and 5/6. StRs rated PBA level 2 demonstrated significantly lower mean total right-hand MLA in comparison to PBA level 4, but not level 3.

Femoral cement preparation

StRs from the intervention group demonstrated significantly lower mean right-hand MLA in comparison to the control group. PGY 1/2 demonstrated significantly lower mean right-hand MLA in comparison to PGY 3/4, but not 5/6. PGY 3/4 demonstrated significantly greater mean right-hand MLA in comparison to PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly lower mean right-hand MLA in comparison to STS-THR 20-39, but not >40. StRs with STS-THR 20-39 demonstrated significantly greater mean right-hand MLA in comparison to STS-THR >40. StRs rated PBA level 2 demonstrated significantly lower mean total right- and left- hand MLA in

comparison to PBA level 3, but not level 4. StRs rated PBA level 3 demonstrated significantly greater mean total right- and left- hand MLA in comparison to PBA level 4.

Femoral canal cementing

PGY 1/2 demonstrated significantly greater mean right- and left- hand MLA in comparison to PGY 3/4, and greater mean right-hand MLA than PGY 5/6. PGY 3/4 demonstrated significantly lower left- hand MLA in comparison to PGY 5/6.

Surgical closure

StRs from the intervention group demonstrated significantly lower mean right-hand MLA in comparison to the control group. PGY 1/2 demonstrated significantly lower mean right-hand MLA in comparison to PGY 3/4, but not 5/6. PGY 3/4 demonstrated significantly greater mean right-hand MLA in comparison to PGY 5/6. StRs with STS-THR 0-19 demonstrated significantly lower mean right-hand MLA in comparison to STS-THR 20-39, but not >40. StRs with STS-THR 20-39 demonstrated significantly greater mean right-hand MLA in comparison to STS-THR >40.

Table 8-23: MLA of hand movements in relation to StR group.

	Right hand				Left hand			
	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]	**Overall**, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Median average over operation								
	0.0008 (0.0005)	0.0006 (0.0003)	0.0009 (0.0005)	**0.010**	0.0005 (0.0004)	0.0006 (0.0005)	0.0005 (0.0003)	0.9
Unknown	6	4	2		6	4	2	
Median average per step								
Approach	0.0003 (0.0003)	0.0003 (0.0003)	0.0003 (0.0003)	0.4	0.0002 (0.0003)	0.0002 (0.0003)	0.0002 (0.0002)	0.6
Unknown	1	1	0		1	1	0	
Hip dislocation	0.0009 (0.0017)	0.0011 (0.0019)	0.0008 (0.0016)	0.7	0.0010 (0.0017)	0.0010 (0.0017)	0.0010 (0.0017)	0.3
Unknown	2	1	1		2	1	1	
Femoral neck osteotomy	0.0021 (0.0039)	0.0013 (0.0018)	0.0028 (0.0051)	0.12	0.0024 (0.0039)	0.0026 (0.0052)	0.0022 (0.0023)	0.3
Unknown	1	0	1		1	0	1	
Acetabular exposure	0.0015 (0.0014)	0.0011 (0.0010)	0.0019 (0.0015)	**0.037**	0.0011 (0.0017)	0.0014 (0.0022)	0.0008 (0.0007)	>0.9
Unknown	1	0	1		1	0	1	
Acetabular reaming	0.0013 (0.0011)	0.0009 (0.0008)	0.0016 (0.0013)	**0.026**	0.0016 (0.0023)	0.0014 (0.0020)	0.0017 (0.0026)	0.5
Acetabular implantation	0.0019 (0.0025)	0.0018 (0.0029)	0.0020 (0.0021)	0.059	0.0014 (0.0033)	0.0018 (0.0047)	0.0011 (0.0013)	>0.9
Unknown	2	2	0		2	2	0	
Femoral broaching	0.009 (0.005)	0.008 (0.006)	0.010 (0.005)	0.2	0.008 (0.014)	0.013 (0.019)	0.004 (0.003)	**0.027**
Unknown	1	1	0		1	1	0	
Initial trial	0.0042 (0.0061)	0.0049 (0.0087)	0.0036 (0.0028)	0.6	0.0063 (0.0262)	0.0119 (0.0396)	0.0020 (0.0014)	0.2
Unknown	6	5	1		6	5	1	
Femoral cement preparation	0.005 (0.005)	0.004 (0.006)	0.006 (0.003)	**0.005**	0.004 (0.005)	0.005 (0.006)	0.003 (0.002)	>0.9
Unknown	11	4	7		11	4	7	
Femoral cementing	0.0004 (0.0009)	0.0005 (0.0012)	0.0003 (0.0005)	0.5	0.0004 (0.0008)	0.0005 (0.0010)	0.0002 (0.0004)	0.063
Unknown	6	1	5		10	4	6	
Femoral stem insertion	0.002 (0.004)	0.002 (0.003)	0.002 (0.005)	0.4	0.0013 (0.0032)	0.0009 (0.0017)	0.0016 (0.0042)	0.13
Unknown	1	1	0		1	1	0	
Definitive trial	0.003 (0.004)	0.003 (0.005)	0.003 (0.003)	0.4	0.0018 (0.0020)	0.0022 (0.0024)	0.0015 (0.0015)	0.5
Unknown	4	3	1		4	3	1	
Closure	0.0006 (0.0005)	0.0004 (0.0003)	0.0007 (0.0006)	**0.003**	0.0002 (0.0001)	0.0003 (0.0002)	0.0002 (0.0001)	0.8
Unknown	2	2	0		2	2	0	

[1] Mean (SD)

[2] Wilcoxon rank sum test

Figure 8-17: MLA of hand movements in relation to StR group.

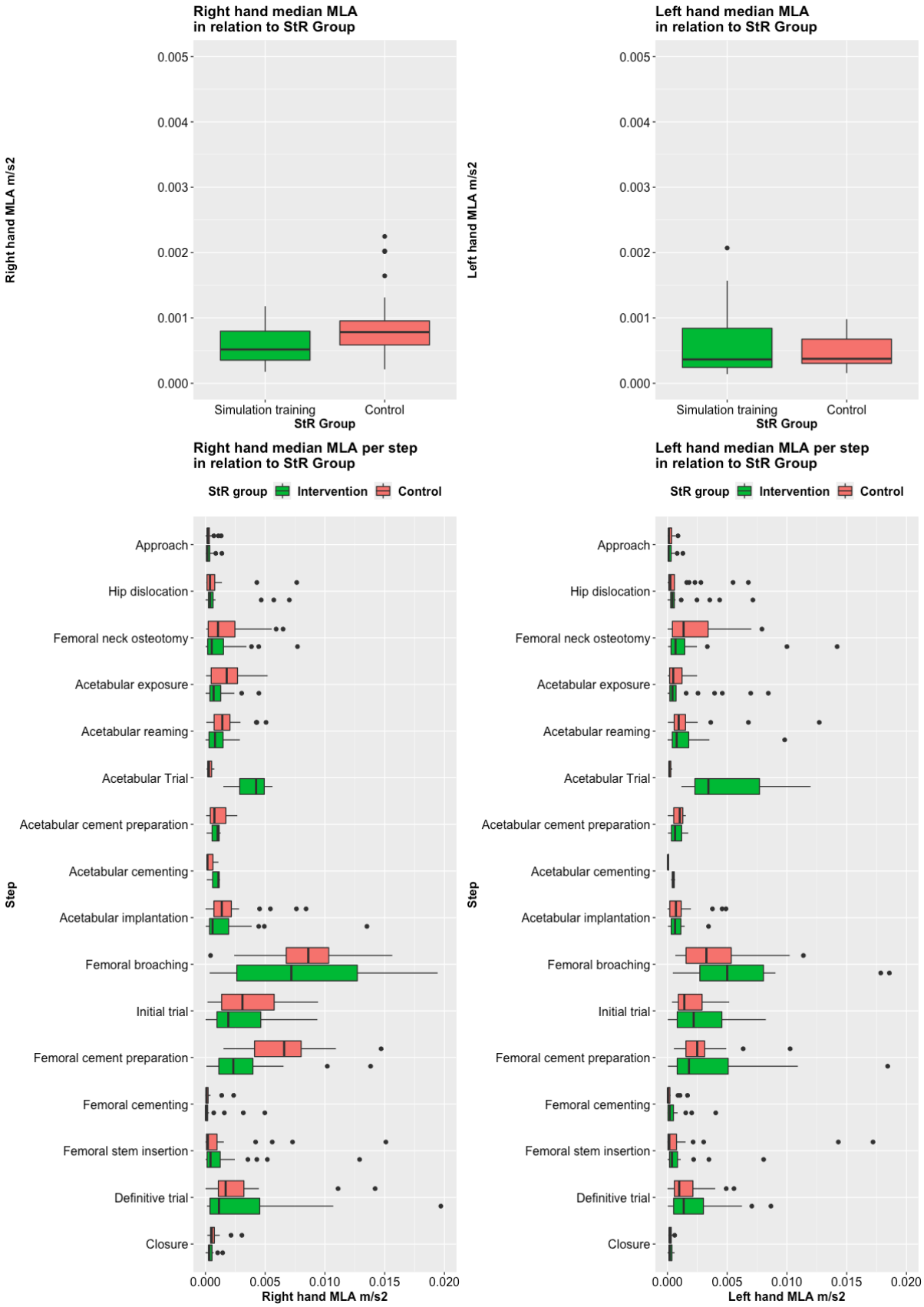


Table 8-24: MLA of hand movements in relation to StR PGY.

	Right hand					Left hand				
	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]	**Overall**, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Median average over operation										
	0.0008 (0.0005)	0.0005 (0.0003)	0.0009 (0.0005)	0.0006 (0.0003)	**0.016**	0.0005 (0.0004)	0.0003 (0.0001)	0.0005 (0.0003)	0.0007 (0.0006)	0.2
Unknown	6	2	4	0		6	2	4	0	
Median average per step										
Approach	0.0003 (0.0003)	0.0003 (0.0004)	0.0004 (0.0003)	0.0002 (0.0002)	0.053	0.0002 (0.0003)	0.0002 (0.0004)	0.0003 (0.0002)	0.0002 (0.0002)	0.13
Unknown	1	0	1	0		1	0	1	0	
Hip dislocation	0.0009 (0.0017)	0.0004 (0.0003)	0.0011 (0.0019)	0.0008 (0.0019)	0.6	0.0010 (0.0017)	0.0003 (0.0002)	0.0013 (0.0020)	0.0007 (0.0011)	0.6
Unknown	2	1	1	0		2	1	1	0	
Femoral neck osteotomy	0.0021 (0.0039)	0.0005 (0.0004)	0.0027 (0.0049)	0.0015 (0.0016)	0.2	0.0024 (0.0039)	0.0006 (0.0007)	0.0027 (0.0042)	0.0029 (0.0043)	0.072
Unknown	1	1	0	0		1	1	0	0	
Acetabular exposure	0.0015 (0.0014)	0.0004 (0.0006)	0.0018 (0.0014)	0.0014 (0.0013)	**0.003**	0.0011 (0.0017)	0.0001 (0.0001)	0.0008 (0.0006)	0.0023 (0.0029)	**<0.001**
Unknown	1	1	0	0		1	1	0	0	
Acetabular reaming	0.0013 (0.0011)	0.0004 (0.0003)	0.0014 (0.0013)	0.0015 (0.0006)	**0.002**	0.0016 (0.0023)	0.0003 (0.0002)	0.0016 (0.0025)	0.0024 (0.0024)	**<0.001**
Acetabular implantation	0.0019 (0.0025)	0.0010 (0.0014)	0.0023 (0.0030)	0.0016 (0.0016)	0.2	0.0014 (0.0033)	0.0003 (0.0003)	0.0012 (0.0013)	0.0025 (0.0063)	**0.024**
Unknown	2	0	2	0		2	0	2	0	
Femoral broaching	0.009 (0.005)	0.005 (0.004)	0.009 (0.005)	0.011 (0.006)	**0.016**	0.008 (0.014)	0.003 (0.002)	0.008 (0.015)	0.013 (0.013)	**0.009**
Unknown	1	0	1	0		1	0	1	0	
Initial trial	0.0042 (0.0061)	0.0013 (0.0019)	0.0050 (0.0072)	0.0039 (0.0032)	**0.019**	0.0063 (0.0262)	0.0010 (0.0014)	0.0087 (0.0329)	0.0031 (0.0026)	**0.014**
Unknown	6	1	1	4		6	1	1	4	
Femoral cement preparation	0.005 (0.005)	0.003 (0.003)	0.006 (0.004)	0.004 (0.008)	**0.009**	0.004 (0.005)	0.002 (0.002)	0.004 (0.005)	0.004 (0.006)	0.5
Unknown	11	1	7	3		11	1	7	3	
Femoral cementing	0.0004 (0.0009)	0.0013 (0.0017)	0.0002 (0.0005)	0.0001 (0.0002)	**0.011**	0.0004 (0.0008)	0.0012 (0.0014)	0.0002 (0.0004)	0.0003 (0.0003)	**0.004**
Unknown	6	0	6	0		10	1	6	3	
Femoral stem insertion	0.002 (0.004)	0.001 (0.001)	0.002 (0.005)	0.002 (0.004)	0.6	0.0013 (0.0032)	0.0003 (0.0003)	0.0016 (0.0040)	0.0013 (0.0023)	0.7
Unknown	1	0	1	0		1	0	1	0	
Definitive trial	0.003 (0.004)	0.002 (0.002)	0.003 (0.003)	0.004 (0.006)	>0.9	0.0018 (0.0020)	0.0012 (0.0010)	0.0014 (0.0014)	0.0034 (0.0028)	0.070
Unknown	4	0	2	2		4	0	2	2	
Closure	0.0006 (0.0005)	0.0004 (0.0003)	0.0007 (0.0006)	0.0004 (0.0003)	**0.015**	0.0002 (0.0001)	0.0002 (0.0001)	0.0003 (0.0001)	0.0002 (0.0002)	0.3
Unknown	2	0	2	0		2	0	2	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-18: MLA of hand movements in relation to StR PGY.

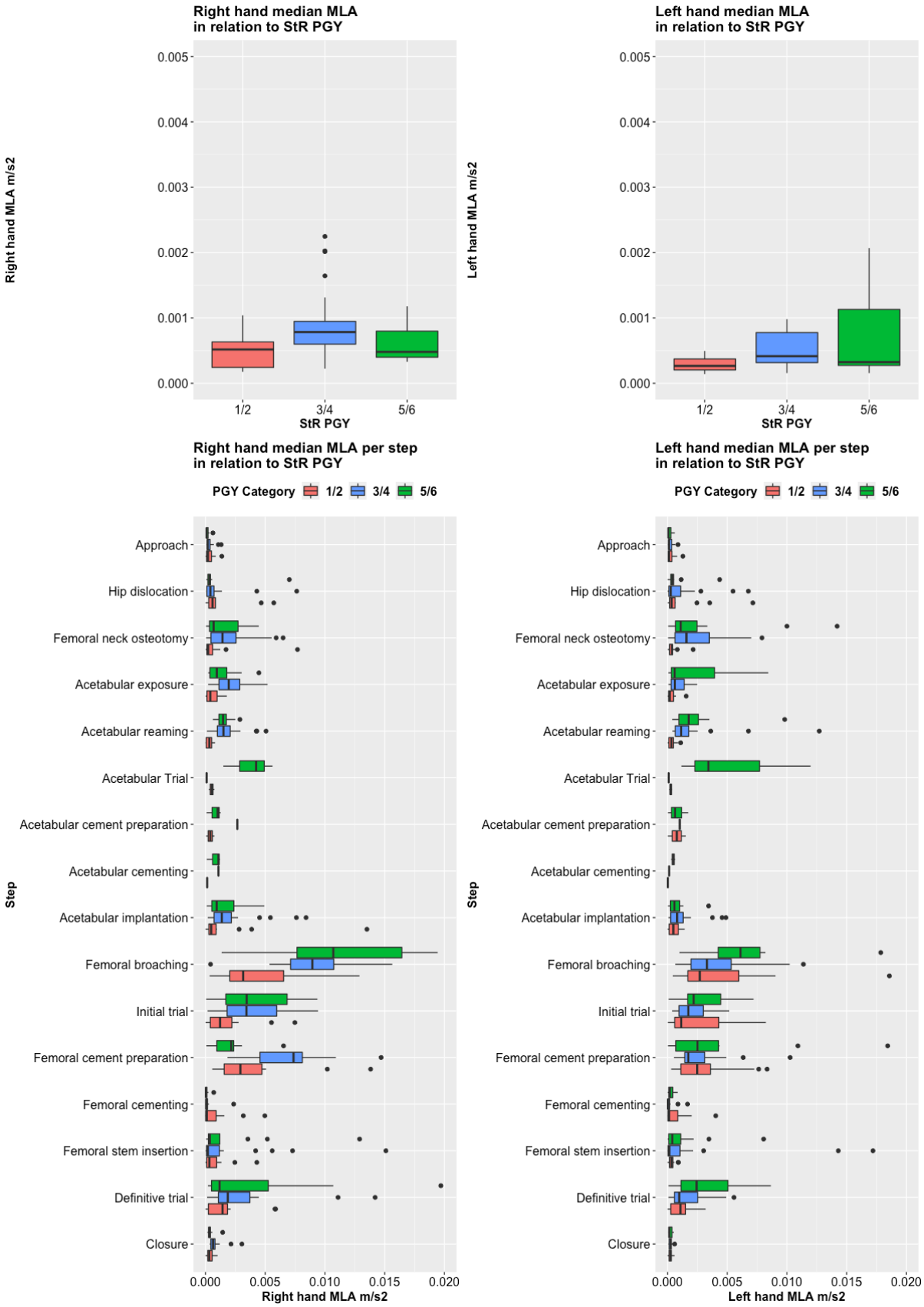


Table 8-25: MLA of hand movements in relation to the total number of supervised THR performed with StR as first surgeon.

	Right hand					Left hand				
	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]	**Overall**, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Median average over operation										
	0.0008 (0.0005)	0.0005 (0.0003)	0.0010 (0.0005)	0.0006 (0.0003)	**0.007**	0.0005 (0.0004)	0.0004 (0.0003)	0.0005 (0.0003)	0.0007 (0.0006)	0.8
Unknown	6	6	0	0		6	6	0	0	
Median average per step										
Approach	0.0003 (0.0003)	0.0004 (0.0004)	0.0003 (0.0003)	0.0002 (0.0002)	0.11	0.0002 (0.0003)	0.0003 (0.0004)	0.0002 (0.0002)	0.0002 (0.0002)	0.3
Unknown	1	1	0	0		1	1	0	0	
Hip dislocation	0.0009 (0.0017)	0.0011 (0.0018)	0.0009 (0.0017)	0.0008 (0.0019)	0.5	0.0010 (0.0017)	0.0012 (0.0020)	0.0011 (0.0018)	0.0007 (0.0011)	0.9
Unknown	2	2	0	0		2	2	0	0	
Femoral neck osteotomy	0.0021 (0.0039)	0.0009 (0.0019)	0.0031 (0.0054)	0.0015 (0.0016)	**0.022**	0.0024 (0.0039)	0.0019 (0.0056)	0.0024 (0.0023)	0.0029 (0.0043)	**0.011**
Unknown	1	1	0	0		1	1	0	0	
Acetabular exposure	0.0015 (0.0014)	0.0006 (0.0006)	0.0022 (0.0014)	0.0014 (0.0013)	**<0.001**	0.0011 (0.0017)	0.0003 (0.0004)	0.0008 (0.0007)	0.0023 (0.0029)	**0.011**
Unknown	1	1	0	0		1	1	0	0	
Acetabular reaming	0.0013 (0.0011)	0.0003 (0.0003)	0.0018 (0.0013)	0.0015 (0.0006)	**<0.001**	0.0016 (0.0023)	0.0004 (0.0003)	0.0020 (0.0027)	0.0024 (0.0024)	**<0.001**
Acetabular implantation	0.0019 (0.0025)	0.0018 (0.0036)	0.0022 (0.0022)	0.0016 (0.0016)	0.052	0.0014 (0.0033)	0.0006 (0.0005)	0.0012 (0.0014)	0.0025 (0.0063)	0.4
Unknown	2	2	0	0		2	2	0	0	
Femoral broaching	0.009 (0.005)	0.004 (0.004)	0.010 (0.005)	0.011 (0.006)	**<0.001**	0.008 (0.014)	0.010 (0.021)	0.004 (0.003)	0.013 (0.013)	0.058
Unknown	1	1	0	0		1	1	0	0	
Initial trial	0.0042 (0.0061)	0.0047 (0.0104)	0.0039 (0.0028)	0.0039 (0.0032)	0.2	0.0063 (0.0262)	0.0151 (0.0474)	0.0021 (0.0014)	0.0031 (0.0026)	0.8
Unknown	6	2	0	4		6	2	0	4	
Femoral cement preparation	0.005 (0.005)	0.004 (0.004)	0.007 (0.003)	0.004 (0.008)	**0.003**	0.004 (0.005)	0.004 (0.005)	0.003 (0.002)	0.004 (0.006)	>0.9
Unknown	11	2	6	3		11	2	6	3	
Femoral cementing	0.0004 (0.0009)	0.0008 (0.0015)	0.0002 (0.0005)	0.0001 (0.0002)	0.3	0.0004 (0.0008)	0.0007 (0.0012)	0.0002 (0.0004)	0.0003 (0.0003)	0.12
Unknown	6	1	5	0		10	2	5	3	
Femoral stem insertion	0.002 (0.004)	0.001 (0.001)	0.003 (0.006)	0.002 (0.004)	0.6	0.0013 (0.0032)	0.0004 (0.0003)	0.0018 (0.0045)	0.0013 (0.0023)	0.6
Unknown	1	1	0	0		1	1	0	0	
Definitive trial	0.003 (0.004)	0.002 (0.002)	0.003 (0.003)	0.004 (0.006)	0.3	0.0018 (0.0020)	0.0012 (0.0010)	0.0014 (0.0014)	0.0034 (0.0028)	0.070
Unknown	4	1	1	2		4	0	2	2	
Closure	0.0006 (0.0005)	0.0004 (0.0003)	0.0008 (0.0006)	0.0004 (0.0003)	**<0.001**	0.0002 (0.0001)	0.0003 (0.0002)	0.0002 (0.0001)	0.0002 (0.0002)	0.7
Unknown	2	2	0	0		2	2	0	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-19: MLA of hand movements in relation to the total number of supervised THR performed with StR as first surgeon.

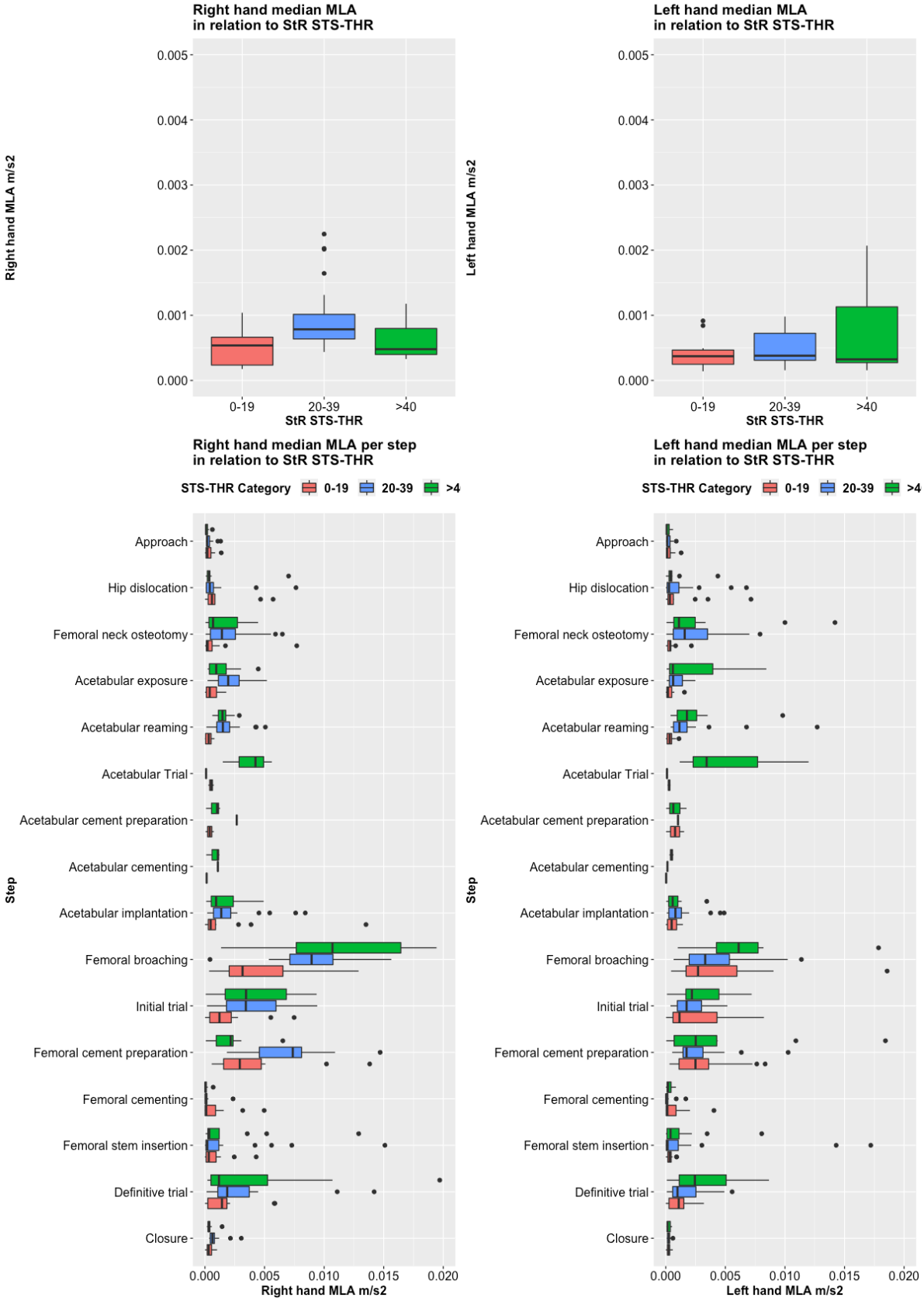


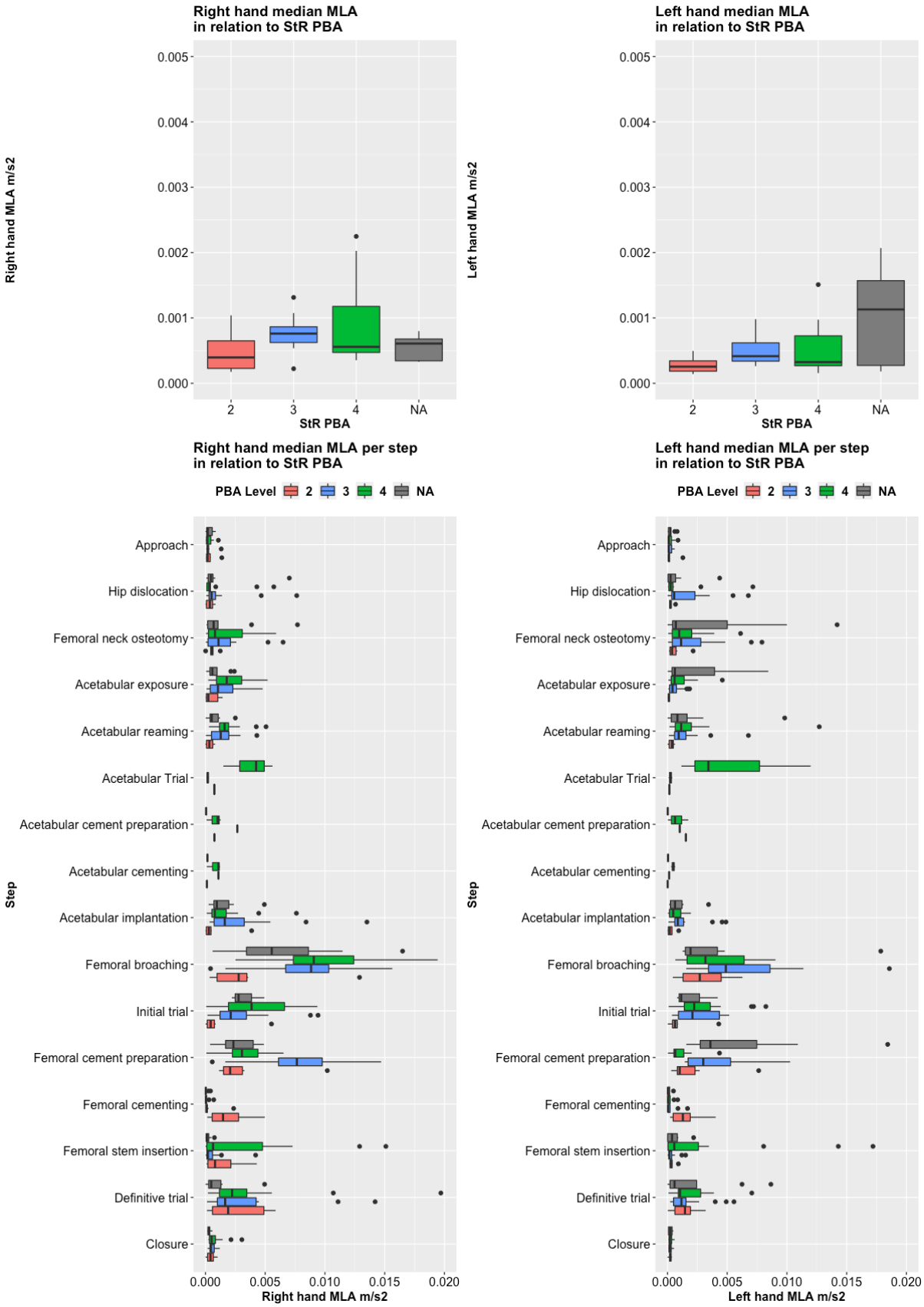
Table 8-26: MLA of hand movements in relation to StR PBA level.

	Right hand					Left hand				
	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	p-value[2]	**Overall**, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	p-value[2]
Median average over operation										
	0.0008 (0.0005)	0.0005 (0.0003)	0.0008 (0.0002)	0.0009 (0.0006)	0.13	0.0005 (0.0003)	0.0003 (0.0001)	0.0005 (0.0002)	0.0005 (0.0004)	0.086
Unknown	1	0	1	0		1	0	1	0	
Median average per step										
Approach	0.0003 (0.0003)	0.0004 (0.0005)	0.0003 (0.0003)	0.0003 (0.0003)	>0.9	0.0002 (0.0003)	0.0003 (0.0005)	0.0002 (0.0002)	0.0002 (0.0002)	>0.9
Hip dislocation	0.0009 (0.0016)	0.0004 (0.0003)	0.0012 (0.0020)	0.0008 (0.0015)	0.13	0.0010 (0.0017)	0.0003 (0.0002)	0.0016 (0.0020)	0.0008 (0.0017)	**0.044**
Femoral neck osteotomy	0.0021 (0.0042)	0.0006 (0.0004)	0.0030 (0.0062)	0.0018 (0.0020)	0.5	0.0017 (0.0019)	0.0007 (0.0008)	0.0021 (0.0024)	0.0016 (0.0016)	0.3
Acetabular exposure	0.0016 (0.0014)	0.0005 (0.0006)	0.0014 (0.0013)	0.0021 (0.0015)	**0.015**	0.0008 (0.0009)	0.0001 (0.0001)	0.0007 (0.0006)	0.0011 (0.0011)	**0.003**
Acetabular reaming	0.0014 (0.0012)	0.0004 (0.0003)	0.0013 (0.0011)	0.0018 (0.0012)	**0.005**	0.0015 (0.0022)	0.0003 (0.0002)	0.0015 (0.0016)	0.0019 (0.0028)	**0.009**
Acetabular implantation	0.0020 (0.0027)	0.0008 (0.0015)	0.0030 (0.0035)	0.0015 (0.0018)	**0.014**	0.0009 (0.0011)	0.0003 (0.0004)	0.0014 (0.0015)	0.0007 (0.0006)	**0.039**
Unknown	1	0	1	0		1	0	1	0	
Femoral broaching	0.009 (0.005)	0.004 (0.005)	0.009 (0.005)	0.011 (0.005)	**0.024**	0.005 (0.004)	0.003 (0.002)	0.006 (0.004)	0.005 (0.005)	0.094
Initial trial	0.0034 (0.0029)	0.0012 (0.0021)	0.0028 (0.0027)	0.0045 (0.0029)	**0.010**	0.0025 (0.0020)	0.0011 (0.0016)	0.0024 (0.0017)	0.0029 (0.0023)	0.053
Femoral cement preparation	0.005 (0.004)	0.003 (0.003)	0.008 (0.004)	0.003 (0.002)	**0.010**	0.0027 (0.0026)	0.0022 (0.0028)	0.0040 (0.0027)	0.0011 (0.0012)	**0.001**
Unknown	9	0	1	8		9	0	1	8	
Femoral cementing	0.0005 (0.0010)	0.0019 (0.0018)	0.0002 (0.0006)	0.0001 (0.0002)	**0.002**	0.0004 (0.0008)	0.0015 (0.0014)	0.0002 (0.0004)	0.0002 (0.0003)	**0.006**
Unknown	5	0	1	4		8	0	1	7	
Femoral stem insertion	0.002 (0.005)	0.001 (0.002)	0.001 (0.001)	0.004 (0.007)	0.3	0.0014 (0.0035)	0.0004 (0.0003)	0.0003 (0.0004)	0.0027 (0.0050)	0.5
Definitive trial	0.003 (0.004)	0.003 (0.003)	0.003 (0.004)	0.004 (0.005)	0.7	0.0017 (0.0016)	0.0014 (0.0011)	0.0017 (0.0017)	0.0019 (0.0018)	>0.9
Unknown	3	0	0	3		3	0	0	3	
Closure	0.0006 (0.0005)	0.0005 (0.0004)	0.0005 (0.0002)	0.0008 (0.0007)	0.5	0.0002 (0.0001)	0.0002 (0.0001)	0.0002 (0.0001)	0.0003 (0.0002)	0.9

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Figure 8-20: MLA of hand movements in relation to StR PBA level.



4) Acetabular cup implantation and femoral stem broaching mallet blow count and MLA

Acetabular cup implantation

Data for calculating the number and MLA of mallet blows of StRs when implanting an uncemented acetabular cup during a primary elective THR was available for 29 (55.8%) and 49 (94.2%) cases, respectively. Only a single reading for acetabular cup implantation was available for PGY 1/2 (11.1%), 4 readings for STS-THR 0-19 (25%), and no readings for StRs rated PBA level 2. The mean number of blows when implanting an uncemented acetabular cup during a primary elective THR across all StRs was 49. StRs from the intervention group were observed to have significantly lower mean number of blows during acetabular cup impaction (n=33) in comparison to the control group (n=59, p=0.011). PGY 3/4 were observed to have significantly higher number of blows (n=56) when implanting an uncemented acetabular cup in comparison to PGY 5/6 (n=35, p=0.045), but not PGY 1/2 (n=16, p=0.075). StRs with STS-THR 20-39 were observed to have significantly higher number of blows (n=62) in comparison to STS-THR 0-19 (n=24; p=0.0089), and STS-THR >40 (n=35; p=0.017). The median MLA of blows during acetabular cup implantation across all StRs was 1,955m/s^2. StRs rated as PBA level 3 were observed to have significantly higher median MLA of mallet blows (5,783m/s^2) in comparison to PBA level 4 (328m/s^2; p=0.012).

Femoral broaching

Data for calculating the number and MLA of mallet blows when broaching the femoral canal during a primary elective THR was available for 49 (94.2%) and 51 (98.1%) cases, respectively. The mean number of blows when broaching the femoral canal during a primary elective THR across all StRs was 122. No significant relationship was observed between the StR group, PGY, or number of STS-THR performed and the number of blows during femoral broaching. StRs rated as PBA level 2 were observed to have significantly higher mean number of mallet blows (n=202) in comparison to PBA level 4 (n=84; p=0.0069), but not PBA level 3 (n=147, p=0.28). StRs rated as PBA level 3 were also observed to have significantly higher mean number of blows in comparison to PBA level 4 (p=0.0084). The median MLA of blows when broaching the femoral canal across all StRs was

297m/s^2. No significant relationship was observed between the StR group, PGY, number of STS-THR performed, or PBA level and the median MLA of mallet blows when broaching the femur.

Table 8-27: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to StR group.

	Impaction Count				Linear deceleration (ms2)			
	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]	**Overall**, N = 52[3]	**Simulation training**, N = 25[3]	**Control**, N = 27[3]	**p-value**[2]
Acetabular Cup Impaction								
	49 (33)	33 (25)	59 (34)	**0.011**	1,955 (322,9,762)	5,193 (1,509,17,299)	832 (241,7,595)	0.2
Unknown	23	14	9		22	14	8	
Femoral Stem Broaching								
	122 (66)	120 (65)	125 (68)	>0.9	297 (210,481)	364 (232,573)	277 (204,424)	0.2
Unknown	3	2	1		1	1	0	

[1] Mean (SD)
[2] Wilcoxon rank sum test
[3] Median (25%,75%)

Table 8-28: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to StR PGY.

	Impaction Count					Linear deceleration (ms2)				
	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]	**Overall**, N = 52[3]	**1/2**, N = 9[3]	**3/4**, N = 30[3]	**5/6**, N = 13[3]	**p-value**[2]
Acetabular Cup Impaction										
	49 (33)	16 (NA)	56 (33)	35 (30)	**0.040**	1,955 (322,9,762)	8,537 (8,537,8,537)	912 (246,5,783)	7,812 (674,44,146)	0.4
Unknown	23	8	10	5		22	8	9	5	
Femoral Stem Broaching										
	122 (66)	149 (90)	126 (66)	101 (43)	0.7	297 (210,481)	338 (224,413)	286 (222,528)	322 (206,430)	>0.9
Unknown	3	2	1	0		1	0	1	0	

[1] Mean (SD)
[2] Kruskal-Wallis rank sum test
[3] Median (25%,75%)

Table 8-29: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to the total number of supervised THR performed with StR as first surgeon.

	Impaction Count					Linear deceleration (ms2)				
	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]	**Overall**, N = 52[3]	**0-19**, N = 16[3]	**20-39**, N = 23[3]	**>40**, N = 13[3]	**p-value**[2]
Acetabular Cup Impaction										
	49 (33)	24 (6)	62 (33)	35 (30)	**0.006**	1,955 (322,9,762)	4,769 (3,371,6,472)	778 (239,5,598)	7,812 (674,44,146)	0.3
Unknown	23	12	6	5		22	12	5	5	
Femoral Stem Broaching										
	122 (66)	130 (76)	131 (70)	101 (43)	0.7	297 (210,481)	353 (275,527)	277 (204,481)	322 (206,430)	0.6
Unknown	3	3	0	0		1	1	0	0	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

[3] Median (25%,75%)

Table 8-30: Impaction count and MLA of mallet blows during acetabular cup impaction and femoral stem broaching in relation to StR PBA level.

	Impaction Count					Linear deceleration (ms2)				
	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]	**Overall**, N = 42[3]	**2**, N = 6[3]	**3**, N = 17[3]	**4**, N = 19[3]	**p-value**[2]
Acetabular Cup Impaction										
	51 (33)	NA (NA)	55 (28)	47 (38)	0.3	912 (316,6,653)	NA (NA,NA)	5,783 (1,686,10,170)	328 (236,852)	**0.012**
Unknown	18	6	5	7		17	6	4	7	
Femoral Stem Broaching										
	123 (71)	202 (87)	147 (68)	84 (46)	**0.004**	288 (210,618)	346 (179,649)	383 (286,713)	237 (175,300)	0.12
Unknown	2	2	0	0						

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

[3] Median (25%,75%)

Figure 8-21: Acetabular cup impaction count in relation to StR group, PGY, and STS-THR.

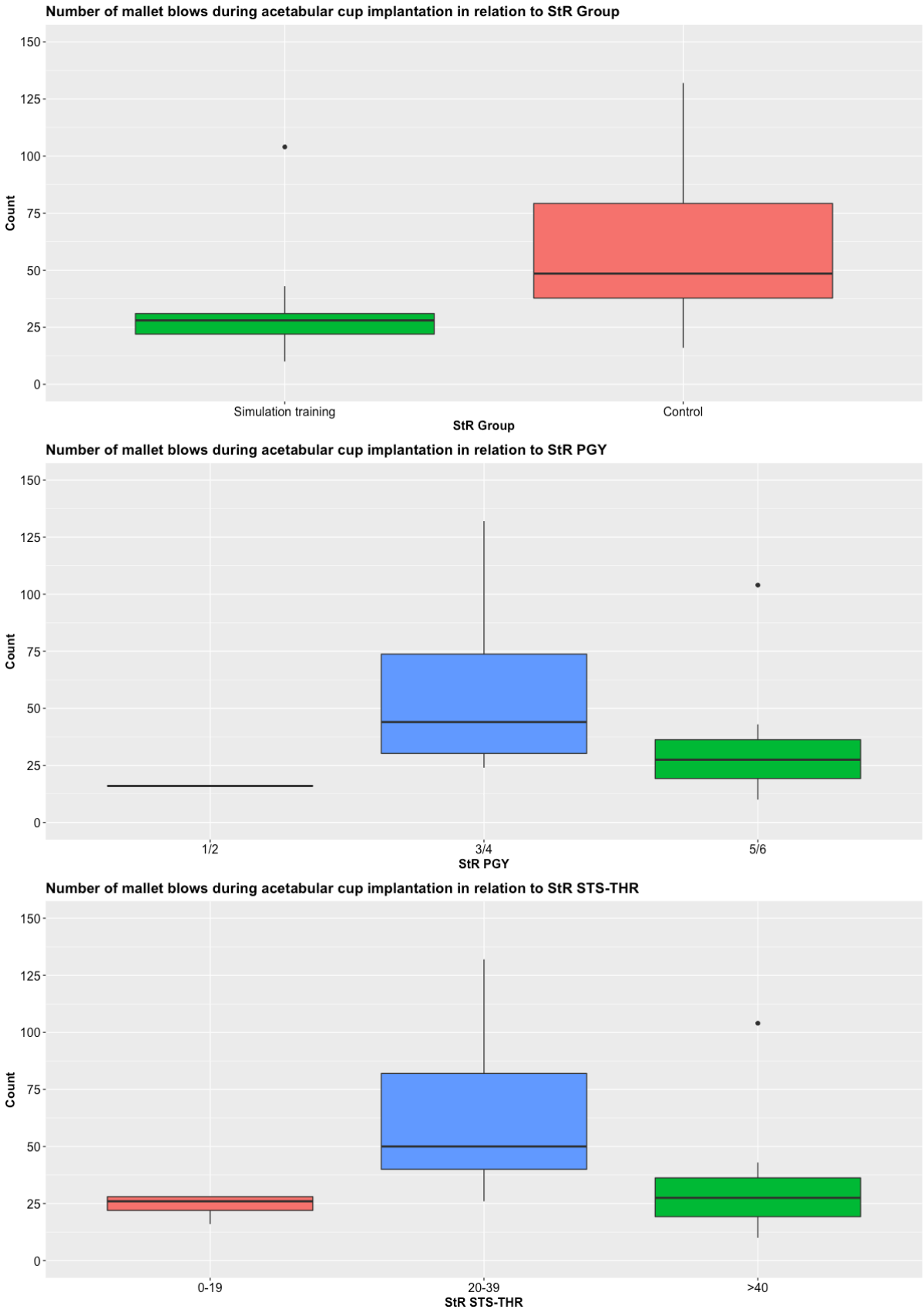


Figure 8-22: Acetabular cup impaction MLA in relation to StR PBA level.

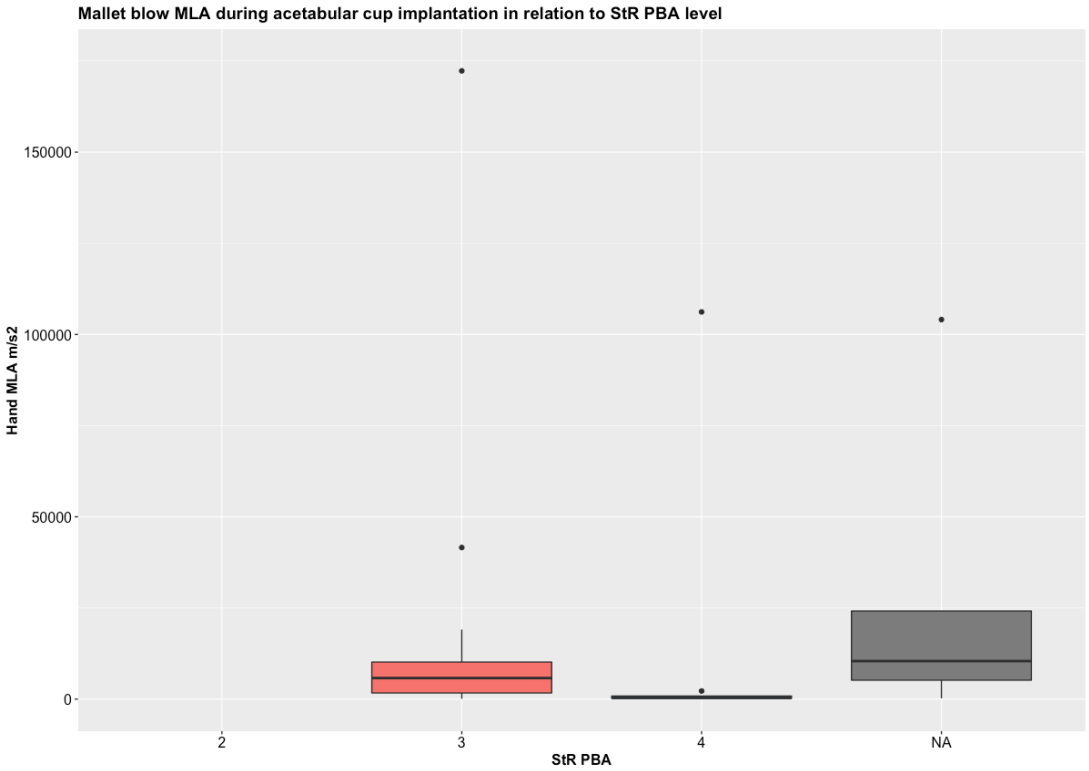
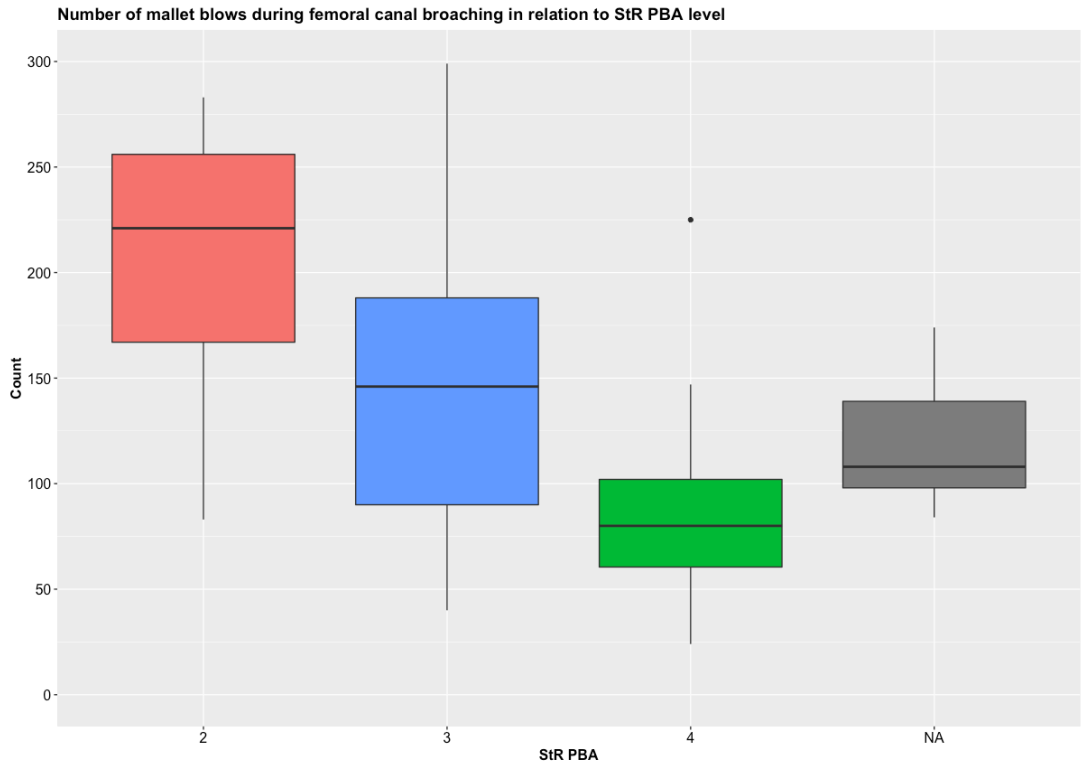


Figure 8-23: Femoral broaching impaction count in relation to StR PBA level



8.3.3.4 Patient-specific metrics

1) Patient-reported outcome measures (PROMs)

Oxford Hip Score (OHS)

Data for calculating the pre- and post-operative OHS was available for 48 (92.3%) cases, and 44 (84.6%) cases, respectively. The mean pre-operative OHS across all StRs was 15, and no significant difference was observed according to StR group (p>0.9), PGY (p=0.31), number of STS-THR performed (p=0.19), or PBA level (p=0.08). The mean post-operative OHS across all StRs was 40.1, and no significant difference was observed according to StR group (p=0.32), PGY (p=0.13), number of STS-THR performed (p=0.43), or PBA level (p=0.061). Tables containing OHS data in relation to StR PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.15.

Table 8-31: Oxford Hip Scores in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline OHS				
	15 (8)	15 (6)	15 (9)	>0.9
Unknown	4	4	0	
3-month follow-up OHS				
	40.1 (6.1)	41.1 (6.0)	39.3 (6.2)	0.3
Unknown	8	6	2	
Change in OHS				
	25 (9)	26 (10)	24 (8)	0.3
Unknown	9	6	3	

[1] Mean (SD)

[2] Wilcoxon rank sum test

EQ-5D 5L VAS

Data for calculating the pre- and post-operative EQ-5D 5L was available for 48 (92.3%) cases, and 44 (84.6%) cases, respectively. The mean pre-operative EQ-5D 5L VAS across all StRs was 57, and no significant difference was observed according to StR group (p>0.9), PGY (p=0.43), number of STS-THR performed (p=0.31), or PBA level (p=0.78). The mean post-operative EQ-5D 5L VAS across all StRs was 75, and no significant difference was observed according to StR group (p>0.9), PGY (p=0.27), number of STS-THR performed (p=0.17), or PBA level (p=0.85). Tables containing EQ-5D 5L VAS data in relation to StR PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.

Table 8-32: EQ-5D 5L VAS in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline EQ5D VAS				
	57 (22)	57 (19)	57 (25)	>0.9
Unknown	4	4	0	
3-month follow-up EQ5D VAS				
	75 (18)	76 (16)	75 (20)	>0.9
Unknown	8	6	2	
Change in EQ5D VAS				
	19 (15)	19 (14)	19 (16)	0.7
Unknown	8	6	2	

[1] Mean (SD)

[2] Wilcoxon rank sum test

EQ-5D 5L Domain 1: Mobility

A significant difference was observed in the median pre-operative mobility domain between patients operated on by StRs from the intervention (simulation training) and control group (p=0.012). No significant differences were observed according to StR PGY, the number of STS-THR performed, or PBA level. A significant difference was observed in the median post-operative mobility domain in relation to StR PGY (p=0.021), but not in relation to StR group, the number of STS-THR performed, or PBA level. No significant differences were observed in the median average change in mobility domain according to StR group, PGY, number of STS-THR performed, or PBA level. Tables containing EQ-5D 5L domain data in relation to StR group, PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.

EQ-5D 5L Domain 2: Self-care

Significant differences were observed in the median pre-operative self-care domain in relation to StR PGY (p=0.022) and the number of STS-THR performed (p=0.031), but not in relation to StR group or PBA level. A significant difference was observed in the median post-operative self-care domain between patients operated on by StRs from the intervention (simulation training) and control group (p=0.013), and in relation to the number of STS-THR performed (p=0.017), but not in relation to PGY, or PBA level. A significant difference was observed in the median average change in self-care domain in relation to StR PBA level (p=0.005), but not in relation to StR group, PGY, or the number of STS-THR performed.

EQ-5D 5L Domain 3: Usual activities

No significant differences were observed in the median pre-operative, post-operative, and change in usual activities domain according to StR group, PGY, number of STS-THR performed, or PBA level.

EQ-5D 5L Domain 4: Pain/discomfort

No significant differences were observed in the median pre-operative, post-operative, and change in pain/discomfort domain according to StR group, PGY, number of STS-THR performed, or PBA level.

EQ-5D 5L Domain 5: Anxiety/depression

Significant differences were observed in the median pre-operative anxiety/depression domain in relation to PGY (p=0.001), the number of STS-THR performed (p=0.0031), and PBA level (p=0.045), but not StR group. No significant differences were observed in the median post-operative anxiety/depression domain according to StR group, PGY, number of STS-THR performed, or PBA level. Significant differences were observed in the median average change in anxiety/depression domain in relation to PGY (p=0.013), the number of STS-THR performed (p=0.0074), but not StR group, or PBA level.

Radiographic analysis

Radiographic analysis was performed on 48 (92.3%) cases. The mean radiographic acetabular cup inclination (RI) across all StRs was 42.7°. No significant difference was observed in the RI according to StR group (p=0.6), PGY (p=0.15), number of STS-THR performed (p=0.14), or PBA level (p=0.2). The mean radiographic acetabular cup anteversion (RA) across all StRs was 16.6°. No significant difference was observed in the RA according to StR group (p=0.3), PGY (p=0.2), number of STS-THR performed (p=0.9), or PBA level (p=0.7). The mean radiographic leg length discrepancy (RLLD) across all StRs was 2.4mm. No significant difference was observed in the RLLD according to StR group (p=0.2), PGY (p=0.4), number of STS-THR performed (p=0.4), or PBA level (p=0.3). The mean radiographic femoral stem alignment (RFSA) across all StRs was 1.2° varus. No significant difference was observed in the RFSA according to StR group (p=0.3), PGY (p=0.4), number of STS-THR performed (p=0.3), or PBA level (p=0.7). The most common Barrack & Harris femoral cementing grade across all StRs was B (n=25, or 64%), indicating radiolucent lines covering up to 50% of the mantle. No significant difference was observed in the Barrack & Harris grade according to StR group (p=0.7), PGY (p=0.9), number of STS-THR performed (p=0.8), or PBA level (p>0.9). Tables containing radiographic analysis data in relation to StR PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.

Table 8-33: Radiographic parameters in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Acetabular Cup Inclination (degrees)				
	42.7 (7.2)	42.2 (6.7)	43.0 (7.7)	0.6
Unknown	4	4	0	
Acetabular Cup Anteversion (degrees)				
	16.6 (7.5)	17.9 (7.4)	15.6 (7.6)	0.3
Unknown	4	4	0	
Radiological Leg Length Discrepancy (mm)				
	2.4 (5.8)	3.6 (5.6)	1.4 (5.9)	0.2
Unknown	5	4	1	
Radiological Femoral Stem Alignment (degrees)				
	1.2 (1.7)	1.0 (2.1)	1.3 (1.4)	0.3
Unknown	4	4	0	
Barrack & Harris Femoral Cementation Grade				
				0.7
A	7 (18%)	4 (22%)	3 (14%)	
B	25 (64%)	12 (67%)	13 (62%)	
C	7 (18%)	2 (11%)	5 (24%)	
Unknown	13	7	6	

[1] Mean (SD)

[2] Wilcoxon rank sum test

2) Blood loss & transfusion requirements

The mean pre-operative Hb across all StRs was 133g/dL. No significant difference was observed in the pre-operative Hb according to StR group (p>0.9), PGY (p=0.9), number of STS-THR performed (p>0.9), or PBA level (p=0.7). The mean post-operative Hb across all surgeon grades was 109g/dL. No significant difference was observed in the post-operative Hb according to StR group (p>0.9), PGY (p=0.7), number of STS-THR performed (p>0.9), or PBA level (p=0.3). The mean on-table blood loss (OTBL) across all operations was 304mls. No significant difference was observed in the OTBL according to StR group (p=0.2), PGY (p=0.13), number of STS-THR performed (p=0.12), or PBA level (p=0.9). Only 1 patient (1.9%) received a blood transfusion. Tables containing the blood loss and transfusion analysis data in relation to StR PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.

Table 8-34: Blood loss & transfusion requirements in relation to surgeon grade.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Pre-op Hb (g/dL)				
	133 (15)	132 (15)	133 (15)	>0.9
Unknown	4	4	0	
Post-op Hb (g/dL)				
	109 (16)	109 (15)	109 (17)	>0.9
Unknown	6	5	1	
Change in Hb (g/dL)				
	-24 (10)	-23 (10)	-24 (9)	0.3
Unknown	6	5	1	
On-Table Blood Loss				
	304 (161)	339 (170)	274 (150)	0.2
Unknown	3	2	1	
Post-op transfusion				
	1 (2.1%)	0 (0%)	1 (3.7%)	>0.9
Unknown	4	4	0	

[1] Mean (SD)

[2] Wilcoxon rank sum test

8.3.3.5 Institutional metrics

Length of stay, re-admissions, and re-operations

Length of stay (LOS) and re-admission/re-operation data was obtained for 48 (92.3%) cases. The mean LOS across all StRs was 3.19 days. No significant differences were observed according to StR group (p=0.6), PGY (p=0.9), number of STS-THR performed (p=0.9), or PBA level (p>0.9). Only a single patient was re-admitted to hospital within 30 days of the index operation (2.1%). StRs rated as PBA level 2 were observed to have a significantly increased incidence of re-admissions in comparison to those rated PBA level 3 or 4 (p=0.046). No significant difference was observed in the incidence of re-admissions according to StR group (p=0.9), PGY (p=0.11), or the number of STS-THR performed (p=0.4). No patient underwent re-operation within 30 days of the index operation. Tables containing the LOS, re-admission, and re-operation data in relation to StR PGY, the number of STS-THR performed, and PBA level may be found in the appendix section E.

Table 8-35: Length of stay, re-admissions, and re-operations in relation to StR group.

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Length of Stay (days)				
	3.19 (2.41)	2.95 (2.20)	3.37 (2.59)	0.6
Unknown	4	4	0	
Re-admission to Hospital within 30days				
	1 (2.1%)	1 (4.8%)	0 (0%)	0.9
Unknown	4	4	0	
Re-operation within 30days				
NO	48 (100%)	21 (100%)	27 (100%)	
Unknown	4	4	0	

[1] Mean (SD)

[2] Wilcoxon rank sum test

8.4 Discussion

8.4.1 Summary and relevance of findings

The combined results of these linked studies represent the most comprehensive and detailed assessment of intra-operative surgeon performance metrics in primary THR within published literature. The combined recruitment of 220 patient- and 23 surgeon-participants is sufficient to adequately power the studies to detect a minimum of 15% difference in operative time between surgeon groups and adds strength to the validity of the findings. The demographics of the patient participants in these studies are representative of patients undergoing primary THR across the UK as reported in the NJR (98), with 69.5% female patients (59.9% in the NJR), a mean patient age of 67.8 years old (median 69 in the NJR), and 81.0% ASA I/II (83.2% in the NJR). The use of hybrid implant fixation was over-represented (65.5%), and both uncemented and cemented fixation under-represented (24.1% and 10.5%, respectively) in these studies in comparison to NJR figures (37.9%, 34.8%, and 22.4%, respectively in 2020). (98) No significant differences were observed in implant fixation in relation to surgeon groups in either study A or B, which justifies using grouped analysis of primary THR cases instead of implant fixation-specific analysis. It was interesting, but not unsurprising, that consultant surgeons were observed to operate on significantly younger patients in comparison to StRs and fellows. This finding has been reported in other studies investigating the impact of surgeon experience on outcomes following THR. (21, 22) This may reflect consultants conscious or unconscious desire to reduce potential intra-operative errors, prolonged operative time, or complications when performing primary THR in younger patients, as enhanced implant survival and function may be perceived as more critical in a younger patient cohort. This finding is also in keeping with the observation that consultants operate on a higher proportion of ASA 1 grade patients (14.8%) and lower proportion of ASA grade 2 patients (67.2%) in comparison to fellows and StRs, as younger patients are generally fitter and healthier than elderly patients. No significant differences were observed in patient gender, age, BMI, or ASA in relation to the StR group in study B. The median of 7 primary THR performed by each StR allows an overview of each participants performance metrics to be represented, and not specific to a single operation.

Operative times in THR

One of the most striking findings of these studies was the stepwise significant reduction in total operating time observed with increasing surgeon experience. This finding confirms that operative time is a sensitive metric in determining the experience of surgeons in THR. Although the mean operative time to perform a primary elective THR across all surgeon grades was 1hour 10minutes and 28seconds, on StRs took 27.2% longer (1hour 17minutes and 58seconds), and fellows took 20.2% (1hour 13minutes and 42seconds) longer to perform a primary THR than consultants (1hour 1minute and 19seconds). The magnitude of time difference per case in relation to lead surgeon grade may be clinically meaningful with respect to productivity when amplified over a full day in theatre. The results suggest that four primary THR performed by consultants would take 4hours and 5minutes of operative time, which is broadly equivalent to three StR performed primary THR at 3hours and 54minutes. Using these figures, a training list of four StR performed primary THR would require approximately 5hours and 12minutes of operative time, which would require time efficiencies in theatre turnaround times between cases. Interestingly the difference in total operative times between surgeon groups was only found to be significant between consultants and both StRs and fellows, and not between StRs and fellows. This suggests that the greatest improvements in operative speed are developed after becoming a consultant, and not during training. Studies have reported mean operative times for trainee-performed primary THR of 78.1 (SD 25.4) (24), 84.3 (SD 16.0) (23), 87.0 (SD 28.3) (25), 100 (26), and 104 minutes (27), and the results of this study are in keeping with the lower end of this range. Significantly longer operative times for trainee-led in comparison to consultant-led primary THR operations have also been reported in previous studies. (24, 25, 26, 27, 28, 29, 30, 326) A systematic review and meta-analysis of seven non-randomised studies (including 40,810 primary THR) reported that trainees took significantly longer to perform THR in comparison to consultants, with a weighted mean difference of 12.9 minutes (95% CI 6.63-19.17, $p < 0.01$). (30) Reducing operative time is important to minimise the incidence of potentially serious complications, including prosthetic joint infection (PJI). Studies have reported an increased risk of PJI in THR lasting greater than 90 minutes, with each 20-minute increase in operative time associated with nearly a 25% increased risk of PJI. (327, 328) No published studies have attempted to determine or

quantify the differences in operative times between surgeon groups based upon the steps of a THR, and this is a novel undertaking within this research. This information may be used as a basis to develop focused simulation training in the steps which trainees struggle to perform intra-operatively. In this study significant differences in operative times between surgeon groups were observed across most steps of a primary THR (n=12/16). On average StRs were observed to be significantly slower than consultants in 9 out of 16 steps, including the surgical approach (51.2% slower); hip dislocation (55.8% slower); femoral neck osteotomy (75% slower); acetabular exposure (39.5% slower); acetabular reaming (26.6% slower), acetabular cup implantation (46.3% slower); initial head trialling (47.0% slower); femoral cementing (15.7% slower); and definitive head trialling (15.9% slower). On average fellows were observed to be significantly slower than consultants in 10 out of 16 steps, including the surgical approach (30.1% slower); hip dislocation (15.4% slower); femoral neck osteotomy (17.3% slower); acetabular exposure (21.4% slower); acetabular reaming (42.1% slower), acetabular cup implantation (23.0% slower); femoral broaching (19.8% slower); femoral cement preparation (15.2% slower); femoral cementing (9.8% slower); and closure (11.1% slower).

No significant differences were observed in the mean total operative time to perform a primary elective THR in relation to the StR group in study B. However, significant differences were observed in the mean total operative time in relation to StR PGY, the number of STS-THR performed, and PBA level. Increasing PGY, STS-THR, and PBA level were all associated with significant reductions in operative times. Significant differences in operative times for the steps of a primary THR in relation to the StR group were only identified in the femoral cementing step, and both the magnitude of difference (mean 18 seconds) and clinical implication of this finding is negligible. However, significant differences in step times were observed in relation to StR PGY, the number of STS-THR, and PBA level in 4/16 (25%), 4/16 (25%), and 3/16 (18.75%) steps, respectively. These steps included the surgical approach, acetabular reaming, femoral broaching, and initial head trialling. Except for femoral broaching, significant differences in step times have been observed between StRs and consultants in the other three steps. This finding suggests that total operating time

may be a sensitive factor in discriminating between the performances of StRs, especially during the surgical approach, acetabular reaming, and initial head trialling steps of a primary THR.

Surgeon movement in THR

Significant reductions in total movement counts were observed with increasing surgeon experience. On average StRs performed 31.4% more and fellows 17.9% more movements to perform a primary THR than consultants. Significant differences were also observed between surgeon groups on pairwise analysis, indicating a high sensitivity and construct validity of this metric in differentiating between surgeons based on their level of experience. Significant differences in movement counts between surgeon groups were also observed across most steps of a primary THR (n=12/16). StRs performed significantly greater movements than consultants in 11 out of 16 steps, including the surgical approach (64.2% increase); hip dislocation (65.3% increase); femoral neck osteotomy (74.5% increase); acetabular exposure (49.6% increase); acetabular reaming (33.3% increase), acetabular cup implantation (49.8% increase); initial head trialling (51.0% increase); femoral cementing (23.3% increase); femoral stem implantation (22.9% increase); definitive head trialling (21.2% increase); and closure (12.6% increase). Fellows demonstrated significantly greater movements than consultants in 9 out of 16 steps, including the surgical approach (29.8% increase); hip dislocation (16.2% increase); femoral neck osteotomy (16.8% increase); acetabular exposure (22.6% increase); acetabular reaming (43.2% increase); acetabular cup implantation (15.1% increase); femoral broaching (22.4% increase); femoral cementing (9.7% increase); and closure (11.6% increase).

No significant differences were observed in the mean total movement counts to perform a primary elective THR in relation to the StR group, or the number of STS-THR in study B. However, significant differences were observed in the mean total movement counts in relation to StR PGY, and PBA level, with increasing PGY and PBA level associated with significant reductions in total movement counts. No significant differences were observed in the mean total movement counts for the steps of a primary THR in relation to the StR group. However, significant differences were

observed in relation to StR PGY, STS-THR, and PBA level in 3/16 (18.75%), 4/16 (25%), and 5/16 (18.75%) steps, respectively. These steps included the surgical approach, acetabular reaming, femoral broaching, femoral cementing, initial head trialling, and closure. Except for femoral broaching and closure, significant differences in movement counts have been observed between StRs and consultants in the other four steps. This finding suggests that total movement counts may be a sensitive factor in discriminating between the performances of StRs, especially during the surgical approach, acetabular reaming, femoral cementing, and initial head trialling steps.

Surgeon MLA in THR

Significant differences in both right- and left-hand median MLA were observed in relation to surgeon group overall, and on pairwise analysis. This finding suggests that MLA is a highly sensitive performance metric which can differentiate between surgeons based on their level of experience. Overall, StRs demonstrated significantly reduced right- and left-hand median MLA (50.0% and 44.4%, respectively) and fellows significantly increased median MLA (37.5% and 44.4%, respectively) in comparison to consultants. The reduced median MLA observed in StRs in comparison to consultants may reflect hesitancy in performing decisive hand movements, and a lack of fluency and progression through the steps of the operation in keeping with their lower level of experience. On the contrary, fellows may be more eager to progress through these steps rapidly as they are likely to possess a better understanding and experience of the instruments and steps of the operation. This may explain the increased median MLA in comparison to consultants, however their movements may remain unrefined and necessitate repeated and potentially quicker movements to complete the intra-operative task. Significant differences in both right- and left-hand median MLA were also observed between surgeon groups across most steps of a primary THR (n=11/16). StRs demonstrated significantly reduced right- and left-hand median MLA in comparison to consultants in 8 out of 16 steps, including the surgical approach (25.0% and 33.3% less, respectively); hip dislocation (67.9% and 66.6% less, respectively); femoral neck osteotomy (50.0% and 33.3% less, respectively); acetabular exposure (50.0% and 31.3% less, respectively); acetabular reaming (80.0% and 60.0% less, respectively), acetabular cup implantation (71.4% and 75.0% less, respectively);

femoral broaching (43.7% and 11.1% less, respectively); and initial head trialling (65.0% and 14.3% less, respectively). Fellows were observed to demonstrate significantly increased right- and left-hand median MLA in comparison to consultants in 6 out of 16 steps, including the surgical approach (75.0% and 100.0% more, respectively); femoral neck osteotomy for left-hand only (166.7% more); acetabular exposure (50.0% and 131.2% more, respectively); femoral cement preparation (33.3% and 66.7% more, respectively); definitive head trialling (100.0% and 54.2% more, respectively); and closure (142.9% and 66.7.2% more, respectively). Fellows were also observed to demonstrate significantly reduced right, but not left-hand MLA in comparison to consultants in the femoral stem implantation stem (-28.6%).

Significant differences in overall right-hand median MLA were observed in relation to the StR group, PGY, and the number of STS-THR in study B. StRs within the intervention group demonstrated significantly reduced overall right-hand average MLA in comparison to the control group. The groupwise differences in relation to StR PGY and the number of STS-THR performed were not observed to follow characteristic stepwise patterns, which may indicate spurious findings, and limit further interpretation. Specifically, StRs in PGY 1/2 and 5/6 demonstrated significantly reduced overall right-hand median MLA in comparison to PGY 3/4. StRs who had logged 0-19 STS-THR or >40 STS-THR demonstrated significantly reduced overall right-hand average MLA in comparison to those who had logged 20-39 STS-THR. No significant differences were observed in the overall left-hand median MLA in relation to StR group, PGY, the number of STS-THR, or PBA level. Significant differences in right-hand median MLA were observed in relation to the StR group, PGY, the number of STS-THR, and PBA level in 4/16 (25%), 6/16 (37.5%), 6/16 (37.5%), and 7/16 (43.75%) steps, respectively. These steps included the femoral neck osteotomy, acetabular exposure, acetabular reaming, acetabular cup implantation, femoral broaching, initial head trialling, femoral cement preparation, femoral cementing, and closure.

Significant differences in left-hand median MLA were observed in relation to the StR group, PGY, the number of STS-THR, and PBA level in 1/16 (6.25%), 6/16 (37.5%), 3/16 (18.75%), and 6/16

(37.5%) steps, respectively. These steps included the hip dislocation, femoral neck osteotomy, acetabular exposure, acetabular reaming, acetabular cup implantation, femoral broaching, initial head trialling, femoral cement preparation, and femoral cementing. Except for femoral cement preparation, femoral cementing and closure, significant differences in right- and left-hand median MLA have been observed between StRs and consultants in the other seven steps. This finding suggests that right- and left-hand median MLA may be sensitive in discriminating between the performances of StRs, especially during the hip dislocation, femoral neck osteotomy, acetabular exposure, acetabular reaming, acetabular cup implantation, femoral broaching, and initial head trialling steps of a primary THR.

Acetabular cup implantation and femoral stem broaching mallet blow count and MLA

Significant differences were observed in the median MLA of mallet blows during both acetabular cup implantation and femoral broaching, and the number of mallet blows during femoral broaching between consultants and fellows. Fellows demonstrated significantly increased median mallet blow MLA in comparison to consultants during acetabular cup implantation (142.3% increase) and femoral broaching (37.0% increase). Fellows also demonstrated significantly increased median mallet blow MLA in comparison to StRs during femoral broaching. Furthermore, fellows demonstrated a significantly increased mean number of mallet blows during femoral broaching in comparison to consultants (40.4% increase). No significant difference was observed in the number of mallet blows during acetabular cup implantation in relation to surgeon group. Furthermore, no significant differences were observed between consultants and StRs in either the mean number of mallet blows during femoral broaching, or the median MLA of mallet blows during acetabular cup implantation or femoral broaching. These findings suggest that the number of mallet blows and MLA are most sensitive in discriminating between fellows and consultants, followed by fellows and StRs, and not useful for discriminating between consultants and StRs. Analysis was not adjusted for the size of femoral broach, which may affect the results as a tighter femoral canal may require more mallet blows to prepare than a capacious canal.

In study B, significant differences in the mean number of mallet blows during acetabular cup impaction were observed in relation to the StR group, PGY, and the number of STS-THR. StRs from the intervention group demonstrated 44.1% less mallet blows during acetabular cup impaction in comparison to the control group (mean n=33 vs n=59). StRs from PGY 3/4 demonstrated 60% more mallet blows during acetabular cup impaction in comparison to PGY 5/6 (mean n=56 vs n=35). StRs with STS-THR 20-39 demonstrated 158.3% more mallet blows during acetabular cup impaction in comparison to STS-THR 0-19 (mean n=62 vs n=24), and 77.1% more mallet blows in comparison to STS-THR>40 (mean n=35). Significant differences were observed in the median MLA of mallet blows during acetabular cup implantation in relation to StR PBA level only, with StRs rated as PBA level 3 demonstrating significantly higher median MLA of mallet blows in comparison to PBA level 4. No significant differences were observed in the median MLA of mallet blows during acetabular cup implantation in relation to StR group, PGY, or the number of STS-THR. No significant relationship was observed in the number of mallet blows during femoral broaching in relation to the StR group, PGY, or number of STS-THR performed. StRs rated as PBA level 2 demonstrated 140.5% more mallet blows in comparison to PBA level 4 (mean n=202 vs n=84), and StRs rated as PBA level 3 demonstrated 86.9% more mallet blows in comparison to PBA level 4 (mean n=157). No significant relationship was observed in the median MLA of mallet blows when broaching the femoral canal in relation to the StR group, PGY, number of STS-THR performed, or PBA level.

PROMS

No significant differences were observed in the mean pre-op, post-op, or peri-operative change in OHS or EQ-5D 5L VAS in relation to surgeon group. Numerous previous studies have also reported no significant difference in PROMs between trainee and consultant led primary THR. (21, 22, 24, 25, 326, 329) In relation to in trainee compared to consultant led primary THR Moran *et al* reported no significant differences in Harris Hip Score (HHS) at 6 and 18 month post-operative timepoints (22); Reidy *et al* reported no significant differences in HHS up to 10 years post-operatively; Palan *et al* reported no significant differences in the change in OHS up to 5 years post-operatively (27); Jolback *et al* reported no significant differences in the change in EQ-5D index or VAS at 1 year post-

operatively (21); and Weber *et al* reported no significant differences in either the Western Ontario and McMaster Universities Arthritis Index (WOMAC) or EQ-5D-5L for minimally invasive primary THR at 1 year post-operatively. (24) The overall mean change in OHS across all surgeon groups in this study was 24 (SD 9), which is over double the minimally important change (MIC) threshold of 11-points (330), almost double the group MIC of 12.4-points (331), and far exceeds the 14-point improvement which is associated with high patient satisfaction at 6-months following THR. (332) Furthermore, the mean change in OHS between each surgeon group was within the 5-point minimally important difference (MID). (330) Published studies have reported significantly increased change in OHS for consultant-led operations in comparison to supervised trainee-led and unsupervised trainee-led operations (20), however, other studies report no significant mean change in OHS between consultant and trainees at three-month follow-up as well as at the one-, two-, three-, four- and five-year follow-ups. (27) No significant differences were observed in the mean pre-op, post-op, or peri-operative change in OHS in relation to StR group, PGY, the number of STS-THR, or PBA level. The overall mean change in EQ-5D 5L VAS across all surgeon groups was 16 (SD 17), which is in keeping with values quoted in published literature. (333, 334) No significant differences were observed in the mean pre-op, post-op, or peri-operative change in any of the five EQ-5D 5L domains, including: 1 (mobility); 2 (self-care); 3 (usual activities); 4 (pain/discomfort); or 5 (anxiety/depression). Although the EQ-5D 5L indices have not been calculated in these studies, the findings support those in published literature, which report equivalent improvements in EQ-5D index following trainee versus consultant led primary THR (0.34+/-0.26 vs 0.32+/-0.23). (24) The findings of these studies do not support the use of either OHS or EQ-5D 5L PROMs for discriminating between surgeons based upon their level of experience. As these PROMs have not demonstrated construct validity in determining surgeon experience in primary THR, the results and interpretation of any changes in OHS and EQ-5D 5L in relation to StR group, PGY, the number of STS-THR, or PBA level in study B are not valid. However, it is noteworthy that StRs rated as PBA level 4 demonstrated significantly higher mean change in OHS (mean change =31) in comparison to those with PBA level 3 (mean change =21).

Radiographic analysis

No significant differences were observed in the mean acetabular cup inclination or version, radiological leg length discrepancy, or quality of femoral cementation in relation to surgeon group. In this study, non-significant reductions in acetabular cup anteversion were observed in trainees. This is in contrast to another study, which reported significantly reduced acetabular cup anteversion in trainee-led primary THR (6.1°) in comparison to consultant-led operations (11.4°) ($p<0.001$). (22) Although consultants were observed to have significantly increased varus femoral stem alignment (2.0° varus) in comparison to StRs (1.2° varus), but not fellows (1.5° varus), clinical studies have reported that slight malalignment (0+/-3º) of femoral stems are not associated with significant adverse patient outcomes following THR. (264, 265) The finding of no significant differences in the quality of femoral cementation between surgeon groups are supported by those reported in a previous case series. (335) The findings of these studies do not support the use of radiological parameters for discriminating between surgeons based upon their level of experience. Furthermore, no significant differences were observed in the acetabular cup inclination or version, radiological leg length discrepancy, femoral stem alignment, or quality of femoral cementation in relation to StR group, PGY, number of STS-THR performed, or PBA level. These findings support those in chapter 2, which highlighted that routine radiological parameters cannot be used in isolation for assessing and defining a trainee's technical skills performance and learning curve in primary THR.

Blood loss and transfusion requirements

No significant differences were observed in the mean pre-op, post-op, or peri-operative change in Hb, OTBL, or in-patient transfusion requirement in relation to surgeon group. The mean OTBL was 316mls (SD 187), with an observed post-operative allogenic blood transfusion rate of 1.7%. This transfusion rate is significantly lower than most published literature. (173, 336, 337, 338) However, patients within these studies received pre-operative intra-venous tranexamic acid (TXA), which is known to reduce both peri-operative blood loss and the incidence of blood transfusions. (336, 339) A single retrospective registry-based study of 13,109 primary THR reported significantly higher transfusion rates in operations performed without a trainee present (12.96%) than when a trainee was

present (11.64%). (173) A registry-based study of 2682 primary THR reported a 30% increase in the risk of requiring a transfusion in trainee performed in comparison to consultant performed operations. (26) Another study reported no significant difference in the incidence of transfusions between trainee and consultant led primary THR. (29) Furthermore, no significant differences were observed in the mean pre-op, post-op, or peri-operative change in Hb, OTBL, or in-patient transfusion requirement in relation to StR group, PGY, number of STS-THR performed, or PBA level.

Length of stay

The mean post-operative patient LOS following primary THR across all surgeon groups was 3.1 days. This is significantly shorter than the LOS reported in most studies (24, 27, 340, 341). Significant differences in patient LOS were observed in relation to surgeon group overall, and on pairwise analysis. Patients undergoing consultant-led operations had significantly shorter mean LOS (2.4 days) in comparison to fellows (3.6 days, p=0.014), but not StRs (3.2 days, p=0.057). This finding contrasts with other published studies, which report no significant differences in the patient LOS following THR performed by trainees or consultants. (24, 27, 30) No significant differences were observed in the incidence of all cause re-admissions to hospital, or re-operations within 30 days of the index operation in relation to surgeon grade. Only a single patient in the fellow-led cohort underwent re-operation (debridement, antibiotics, and implant retention) within 30 days of the index operation for prosthetic joint infection (PJI). A systematic review and meta-analysis of trainee- versus consultant surgeon performed elective THR reported no difference in the incidence of PJI between consultants and trainees. (30) Furthermore, no significant differences were observed in the mean LOS in relation to StR group, PGY, number of STS-THR performed, or PBA level.

8.4.2 Limitations of study

One of the main limitations of this study is that most of the surgeon performance metrics and methods for generating them are novel, including: the movement count; MLA; and mallet blow MLA and count. This limits any direct comparison to other published literature. For this reason, the studies in this chapter were powered using operative time as the primary outcome metric, which has been widely reported in relation to surgeon experience in primary THR. Another pertinent limitation of these studies is that the practice of surgeons when impacting uncemented acetabular cups is variable. Often the primary surgeon undertakes this step, however occasionally they hold the impactor handle and request the first assistant to impact the cup for them. This variation in practice is not captured within these studies and may limit the interpretation of this metric. Similarly, the supervising surgeon may in some instance 'take-over' the operating from trainees during specific steps of a primary THR operation. This may be because they can see that the trainee is struggling, or simply want to complete a perceived difficult step themselves to facilitate progress through the operation. Again, this variation in practice is not fully captured within these studies. To mitigate the effects of this phenomenon, any step which a trainee (StR or fellow) did not complete was excluded from the data analysis. Any potential limitation of these studies is that the surgeon outcome measures used focussed solely on technical skills performance, and not on non-technical skills. Non-technical skills for surgeons (NOTSS), including communication, leadership, teamwork, situational awareness, and decision-making skills are recognised as critically important factors in promoting both patient safety and surgical performance. (342, 343, 344) Future studies may consider incorporating the assessment of these factors as part of the overall assessment of intra-operative surgeon performance. In relation to NOTSS, the role of the scrub staff, operating department practitioners (ODPs), anaesthetic team, and other ancillary theatre staff were also excluded from the analysis in this study. Although it would be difficult to quantify the impact of a specific team of theatre personnel on an individual surgeon performance and patient outcomes in THR, it is reasonable to acknowledge that teams who work regularly with each other undoubtedly outperform a team who rarely work together when performing the same operation. In relation to patient outcomes, the PROMs used in these studies (OHS and EQ-

5D-5L) were chosen specifically as they are utilised to assess patient outcomes following elective joint replacement within joint replacement the NHS and NJR. However, they only represent a fraction of PROMs available, and therefore consideration for using alternative joint-specific or general health measures may be given in future research studies. Major intra- and post-operative complications of primary THR, such as dislocation, prosthetic joint infection, peri-prosthetic fracture, venous thromboembolism, and mortality were not considered within the scope of these studies, as previous findings outlined in chapter 3 and other registry-based studies and a meta-analysis (20, 30, 165, 172, 173) have highlighted the rarity of such complications. Larger scale adequately statistically powered prospective randomised-controlled clinical studies would be required to determine any significant differences in these factors between surgeon groups.

8.5 Conclusions

The findings reported in these linked studies represent an exciting step in exploratory research within the field of intra-operative surgeon performance and assessment in primary elective THR. The results have highlighted several important and statistically significant differences in performance metrics between surgeons in relation to experience. Importantly, recording and analysis of the objective surgeon performance metrics included in these studies (operative time, movement count, and MLA) using the validated wireless motion system outlined in chapter 6 was both feasible and well tolerated by surgeon participants. Segmentation of the overall THR operation into finite steps is a novel undertaking which has provided a detailed insight into intra-operative surgeon performance to be established. This methodology has identified several differences in objective performance metrics between surgeon groups in relation to their level of experience over the entirety and within specific steps of the operation.

The findings of study A have confirmed the construct validity of overall operative time, movement counts, and MLA in differentiating surgeons based upon their level of experience. Stepwise and statistically significant differences were observed in the overall mean operative times and movement

counts between consultants, fellows, and StRs, with non-stepwise but statistically significant differences observed in MLA. Trainees (StRs and fellows) were significantly slower and performed significantly more movements than consultants in most steps of the operation (n=12/16 for both operative times and movement counts). The surgical approach, hip dislocation, femoral neck osteotomy, acetabular exposure, reaming and cup implantation, and femoral cementing steps demonstrated significant differences in these metrics between both StRs and fellows in comparison to consultants. However, differences were also observed in either operative time or movement count during initial and definitive head trialling, femoral broaching and stem implantation, and closure between either StRs or fellows in comparison to consultants. Furthermore, significant differences in MLA were also observed between all trainees and consultants in the surgical approach, femoral neck osteotomy and acetabular exposure steps of the operation. Regards acetabular cup implantation, fellows demonstrated significantly increased median mallet blow MLA in comparison to consultants, but no significant differences were observed between surgeon groups in the number of mallet blows administered. Regards femoral broaching, fellows demonstrated significantly increased median MLA and mean number of mallet blows in comparison to consultants. However, no significant differences were observed between consultants and StRs in either the mean number or median MLA of mallet blows during femoral broaching. These findings suggest that mallet blow count and MLA can discriminate between fellows and consultants, but not between consultants and StRs. Regards the patient-specific metrics studied no significant differences were observed in the mean pre-op, post-op, or peri-operative change in OHS, EQ-5D 5L VAS, haemoglobin levels, OTBL, or any of the post-operative radiographic parameters studied in relation to surgeon group. These findings do not support the use of either PROMs, surrogate markers of blood loss, or post-operative radiographic parameters for discriminating between surgeons performance based upon their level of experience. Patients undergoing consultant-led operations were observed to have significantly shorter mean LOS in comparison to fellows, but not StRs, but no significant differences were observed in the incidence of all cause re-admissions to hospital, or re-operations within 30 days of the index operation in relation to surgeon grade.

The findings of study B did not identify any significant differences in either the mean total operative time or movement counts to perform a primary elective THR in relation to the StR group. Although this suggests that additional simulation training did not result in any significant improvement in intra-operative performance metrics in this cohort of StRs, it must be noted that this was a feasibility study involving a relatively small cohort of seven StRs with a heterogenous spread in training experience (grade and number of STS-THR performed). Surgeons inevitably benefit from different modalities of training dependent upon their prior knowledge and experience. The training profile questionnaire outlined in chapter 7 study B highlights that most trainees (n=30/34, 88.2%) would prefer surgical skills courses to be undertaken in the early stages of their specialty training (ST3/4 level). It is logical to suggest that additional simulation-based training at this early stage would theoretically benefit trainees the more than those in the final stages of their training when their practice and habits are more established. In these studies, only two out of the seven StR participants were ST3/4 level, with one randomised into the intervention and one in the control group. This factor may therefore limit the perceived impact of additional simulation training on the intra-operative performance metrics studied at a group level. Significant differences were observed in both the mean total operative time and movement counts in relation to StR PGY, and PBA level, with increasing PGY and PBA level found to be associated with significant reductions in operative times and movement counts. This suggests that more experienced trainees demonstrate improved intra-operative performance metrics with concomitant improvements in PBA level. The specific steps associated with significant reductions in both operative times and movement counts in relation to StR PGY and PBA level included the surgical approach, acetabular reaming, femoral broaching, and initial head trialling. Although significant differences in MLA were also observed in relation to the StR group, PGY, and the number of STS-THR, the groupwise differences in relation to StR PGY and STS-THR did not follow characteristic stepwise patterns, which limits further inference. Regards acetabular cup implantation, significant differences in the mean number of mallet blows were observed in relation to the StR group, PGY, and the number of STS-THR, with significant differences also observed in the median MLA of mallet blows in relation to StR PBA level only. Regards femoral broaching, significant differences in the mean number of mallet blows were

observed in relation to PBA level alone, with no differences observed in the median MLA of mallet blows in relation to StR group, PGY, number of STS-THR performed, or PBA level. Regards the patient-specific metrics, the lack of construct validity in PROMS, surrogate markers of blood loss, and post-operative radiographic parameters outlined in study A limits any interpretation of differences identified in study B. Furthermore, no significant differences were observed in the mean LOS in relation to StR group, PGY, number of STS-THR performed, or PBA level.

In summary, the overall operative time, movement count, and MLA are all useful and valid metrics for differentiating the intra-operative performance surgeons in THR based upon their level of experience. The main differences in performance metrics between trainees and consultants were observed within the surgical approach, hip dislocation, femoral neck osteotomy, acetabular exposure, reaming and cup implantation, and femoral cementing steps of this operation. Improvements in training should focus on these steps, which may, in turn, result in improved intra-operative performance. However, despite the significant differences observed in the intra-operative performance metrics between consultants, fellows, and StRs, no significant differences were demonstrated in patient outcome metrics between these groups of surgeons. These results support the safety and efficacy of supervised training in THR in relation to patient outcomes.

Operative times remain the easiest metric to record, which also benefit from not requiring any technology, software, or expertise to collect or analyse. However, the role of motion analysis in the objective assessment of surgical performance has been proven in these studies, and further developments and refinement of this technology may increase its future application and scope in the domain of surgical training. When collected, analysed, and interpreted appropriately, objective performance metrics may help guide trainers and trainees alike to reflect upon and develop targeted improvements in personal performance. To maximise the reliability of the findings reported, I believe that further larger scale studies would be extremely valuable in determining the true impact of additional simulation training on StR performance. It may also be useful to establish a national or international repository of surgeon performance data from a collection of different and unique

healthcare environments and patient populations. A centralised surgeon performance database would complement the patient reported outcome measures provided through the NJR and allow both surgeons and surgical trainees to reflect upon and compare their practice and performance against peers and experts in their field.

The research methodology and outcome metrics used in these studies may also be used or expanded for assessing other operations or procedures, not only in the field of orthopaedic surgery, but also more widely in other medical and surgical disciplines. Throughout the course of conducting this research I have been approached by numerous medical colleagues who have enquired about adopting and applying this technology in assessing operator performance within their specialty, and this is encouraging for its future use in the domain of medical training.

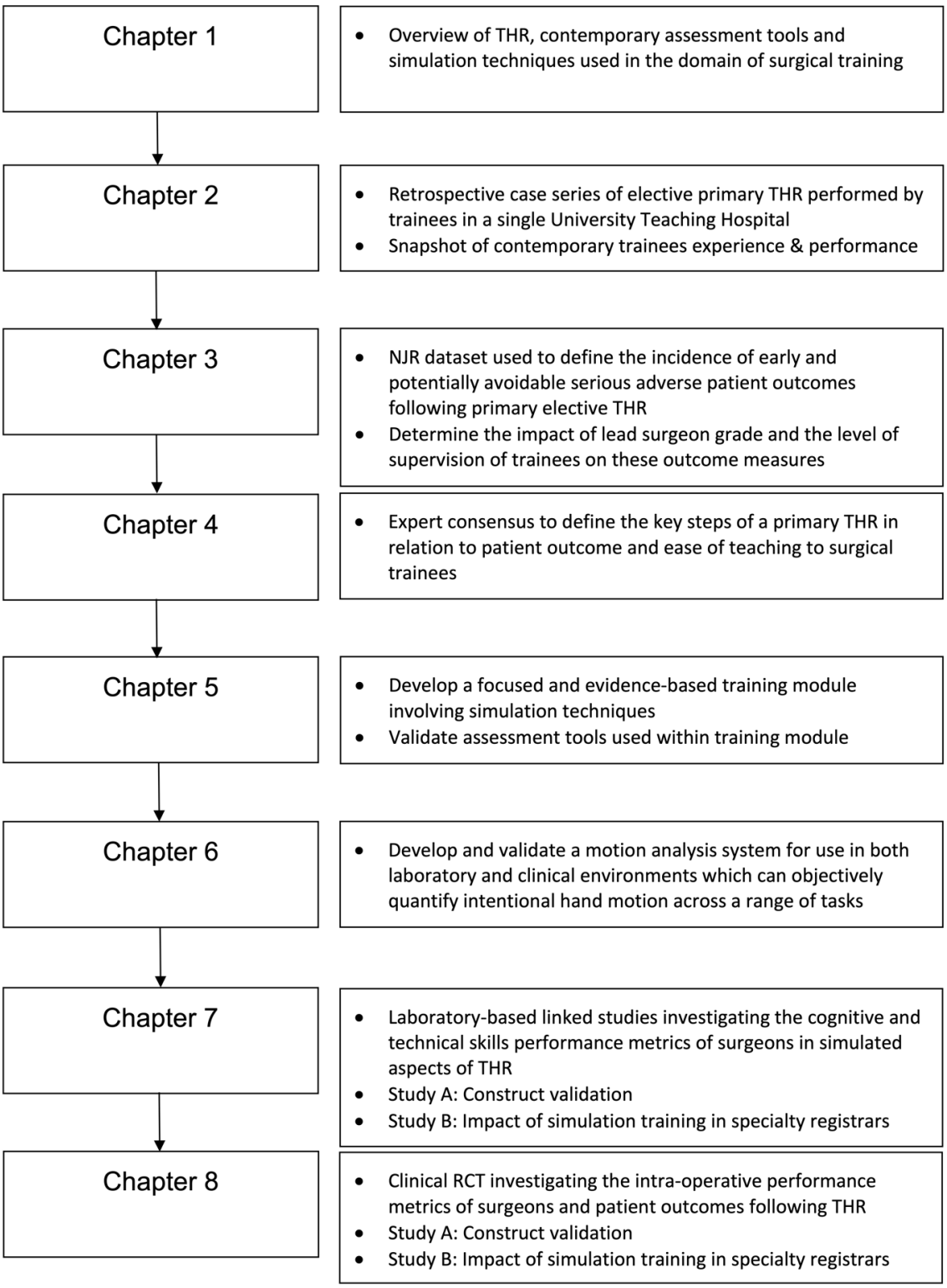
9. Summary results and future work

9.1 Summary results

The original research studies in this thesis have used established and contemporary techniques in both data analysis and simulation training modalities to investigate surgeon performance and patient outcomes in elective primary total hip replacement. Several novel findings have been reported within these studies which collectively advance the scientific knowledge base within this field of research. The literature review conducted in chapter one provides an overview of the contemporary assessment tools and both generic and procedure-specific simulation techniques used in the domain of surgical training. It highlights the importance, technical considerations, and potential complications of THR, which is arguably one of the most performed and effective orthopaedic operations. (10, 12, 95, 97) The retrospective case series of elective primary THR performed in a single University Teaching Hospital outlined in chapter two provides a contemporary insight into trainees experience and performance in this procedure during clinical training. In chapter three, a large dataset extracted from the NJR of England, Wales, Northern Ireland, the Isle of Man and Guernsey was analysed to define the incidence of early and potentially avoidable serious adverse patient outcomes following primary elective THR, and to determine the impact of lead surgeon grade and the level of supervision of trainees on these outcome measures. Expert consensus methodology was used in chapter four to define the key steps of a primary THR in relation to patient outcome and ease of teaching to surgical trainees. The results of this were used in chapter five to develop an evidence-based training module involving simulation techniques which would be delivered to orthopaedic specialty registrars (StRs). The impact of this training module on the cognitive and technical skills performance of orthopaedic StRs in both laboratory-based and real-world environments were then assessed in study chapters seven and eight, respectively. The linked studies in chapters seven and eight also aimed to assess the construct validity of surgeon performance and patient outcome metrics in relation to the surgeons level of experience. The randomised clinical trial in chapter eight used motion analysis techniques and metrics developed and validated in chapter six to investigate intra-operative surgeon

performance and patient outcomes following primary elective THR. A flowchart providing an overview of the structure of this thesis is outlined in figure 9-1.

Figure 9-1: Overview of thesis structure.



The retrospective analysis of primary elective THR operations performed by a cohort of 12 orthopaedic trainees conducted in chapter two demonstrated a lack of sensitivity in using operative times and common radiographic parameters for assessing technical procedural skills and learning curves in trainees across a 6-month clinical placement. The results provided an insight into the expected number of primary THR cases performed by orthopaedic trainees on arthroplasty placements within a 6-month period (median 28, range 15-51). Overall, 62.1% of trainee led primary THRs were performed with a scrubbed supervisor (STS), which differed significantly across the cohort of trainees. This finding suggests that consultants adjust their level of supervision for each trainee, which in turn, likely depends upon the skill and ability demonstrated by individual trainees. It was also interesting to find that operative times were significantly slower when StRs are assisted by other StRs, in comparison to fellows and consultants. Furthermore, the mean operative time for trainee led primary THR of 84.3 minutes was used to calculate the sample size in chapter eight.

One of the most striking findings of chapter three is the significantly increased incidence of early post-operative revision procedures within 1-year of primary THR for operations performed by unsupervised trainees (StRs and fellows) in comparison to either supervised trainees or consultants between 2015-2020. This finding highlights the importance of appropriate consultant supervision during primary THR performed by surgical trainees which may, in conjunction with other reported risk factors, reduce the incidence of potentially avoidable early revision operations. (185, 186) The aetiology of these early failures appears to be driven by an increased incidence of PJI and dislocation/instability for cases performed between 2015-2020 in comparison to previous years. These findings are supported by the results of another recent observational study using NJR data. (165) Across the dataset of 9999 primary THR, 44.7% of cases were performed by trainees, with the majority of trainee led cases (53.7%) being performed unsupervised. This proportion is larger than reported in the retrospective case-series in chapter two (37.9% unsupervised), potentially because the trainee cohort in chapter three included fellows, who are more likely to perform operations without direct consultant supervision. However, a gradual but consistent reduction in the proportion of unsupervised operations was observed from 62.4% between 2005-2010, to 59.2% between 2010-

2015, and 40.8% between 2015-2020. This suggests a conscious or unconscious move by consultants towards increased trainee supervision in primary THR. The reasons for this observation have not been investigated further within the scope of this research, however it may be postulated that it is a measured response to the observed recent increase in early post-operative revisions, which are known to negatively impact on NJR performance and patient outcome figures. An increased drive for consultant led service provision and increased theatre utilisation and productivity may be other factors. The logbook numbers of trainees involved in this research were unknown, and therefore any relationship between their operative experience and incidence of early revision procedures following primary THR is speculative. It is re-assuring to report that no significant differences were identified in the risk of 1-year mortality or all-cause revision between consultant-led, overall trainee-led, or trainee-supervised operations across the entire 15-year data collection period. This finding agrees with other published studies which have reported no significantly increased risk of revision procedures in patients undergoing THR operations performed by trainees in comparison to consultants. (20, 26, 28, 30, 165, 172, 173) Furthermore, the overall incidence of 1-year mortality and all-cause revision following primary THR in this study were low at 2.05% and 1.11%, respectively.

The expert consensus outlined in study chapter four generated a rank order list of the critical steps of a primary THR which a group of experienced hip surgeons considered substantially important to patient outcomes and difficult to teach to trainees clinically. The relatively large number of high-volume expert participants who contributed to this consensus in combination with adherence to pre-determined and robust methodological criteria using a high threshold for defining consensus adds validity to the findings of this study. The results highlighted that acetabular reaming, exposure, and cup orientation (anteversion and inclination), along with the accurate assessment and reconstruction of leg lengths and hip offset were deemed to be the 6 most critical steps for optimising patient outcomes which are also difficult to teach trainees. These are novel findings, which helped guide the content and structure of the simulation-based training module outlined in chapter five. The results from this study chapter have been published, which will allow orthopaedic surgeons who are actively

involved in teaching and training along with their trainees to use the findings as a framework to identify specific areas for personal development. Similarly, local hospitals, regional networks, and even national organisations responsible for developing curricula and delivering post-graduate medical education may decide to enhance both simulation-based and clinical training opportunities in the steps identified as critical to the outcome or perceived as difficult to teach 'on the job'.

Development of the focussed and evidence-based training module outlined in study chapter five was an important step in the overall research project as it formed the intervention delivered to trainees in the subsequent trials within study chapters seven and eight. The rationale for developing this training module was to deliver the core scientific knowledge and theory underpinning a successful primary THR; allow trainees the opportunity to practise key steps of this operation in the safety of a simulated environment prior to refinement of these skills in clinical practice; and use validated methodology to assess performance in the practical technical procedural skills required in the critical steps of this operation. Production and distribution of the delegate workbook was well received by the study participants and may be used as a continuing reference not only for the participants in this research, but also for future trainees during their clinical arthroplasty placements. Except for the component templating exercise, the remaining methods for assessing trainee participants knowledge and technical skills in this study chapter were all novel. The validity of the MCQs and implant orientation exercise were determined using established scientific methodology, which justifies their use and interpretation of results obtained in study chapter seven. Validation of a novel VR platform for determining real-time quantification of both acetabular cup and femoral stem component orientation in simulated THR was unique to this research and highlights the benefits and incorporating emerging digital technology in surgical training. This platform may potentially be adapted refined and applied for both surgical training and research purposes. The use of a simple, low-cost hip simulator for assessing the length and curvature of planned skin incision during standard posterior and Hardinge surgical approaches was a novel technique developed for use in this study. Although no single assessment can fully determine the overall cognitive or technical skill performance level of an individual, the assessment tools specific to primary THR which have been developed within this

study aimed to test a broad range of procedure-specific cognitive and technical procedural skills performance in participants.

Research to develop and validate a low-cost wireless motion analysis system capable of objectively assessing technical surgical skills was a novel undertaking in study chapter six. This research is the first to report on the use of motion analysis techniques and methodology in THR. The ability to determine the number and relative force of mallet blows during uncemented acetabular cup implantation and femoral canal preparation using inertial sensor technology is also a novel research technique. The robust series of content and concurrent validation experiments conducted in these linked studies were performed using a range of simple and task-specific hand movements in both a simulated setting and the real-world environment of the operating theatre. The results demonstrated that movement counts generated by both wired and wireless motion analysis systems are significantly and highly correlated with actual movement counts observed during both simple and complex procedure-specific tasks. The findings also highlight the safety, adaptability, and feasibility of using a wireless motion analysis system in both laboratory and clinical environments.

The linked studies in study chapter seven aimed to investigate the cognitive and technical skills performance metrics of participants during simulated components of a THR; identify any significant differences based upon the participants level of experience (study A); and determine any significant changes in the metrics of orthopaedic trainees following a focussed simulation-based module (study B). Study A identified several differences in the performance metrics between participants in simulated aspects of THR based upon their level of experience (construct validation). StRs, but not fellows, were observed to demonstrate significantly longer skin incision markings than consultants when performing a simulated posterior approach to the hip joint. Although the clinical relevance of this finding is questionable, the relationship between surgical experience and length of skin incision in primary THR has not been previously reported. Although a non-significantly higher proportion of fellows achieved a pass in the MCQ in comparison to StRs (44.4% versus 20.6%, respectively), neither the absolute score or pass rate of the MCQ were able to differentiate between fellow and StR

groups. No significant differences were observed between consultants, fellows, or StRs in the component templating task, which suggests that this is not reliable in differentiating surgeons based upon their level of experience. However, StRs and fellows were both observed to demonstrate a trend towards under sizing the femoral stem offset when templating primary THR in comparison to consultants, which may have important implications for patient outcomes and increase the risk of complications. (101, 116, 119, 120, 121, 122) Although no significant differences in femoral stem anteversion (FSV) were observed between groups during the simulated component orientation exercise, it is interesting finding that 100% of consultants achieved FSV within 5° of the 15° target, in comparison to only 40% of fellows, 64% of StRs, and 57% (4/7) of medical students. Consultants were found to overestimate operative acetabular cup anteversion (OA) by a median average of 13.5° and underestimate operative acetabular cup inclination (OI) by a median average of 1.6° across all pelvic models used in this study. This is less inclination error but more anteversion error than has been reported in other simulation studies. (66, 236) On average, fellows and StRs also overestimated OA by 10.8° and 5.3° respectively. Although fellows underestimated OI by a median average of 0.3°, StRs overestimated OI by a median average of 1.4°. The use of mechanical alignment guides (MAG) reduced the average OA readings by consultants, fellows, and StRs in all models during this study, which may reflect a subconscious desire of surgeons to increase anteversion in the absence of visual or mechanical cues. Overall consultants demonstrated lower median OI in comparison to StRs in 87.5% of models, and higher median OA in comparison to StRs in all models. No significant differences were found in the median average OI between participant groups, and 71% of participants from all four groups achieved OI within 5° of target. However, significant differences were found in the median average OA between participant groups, which was driven by significantly higher OA in the fellow group in comparison to the StR group. Although the MCQ and component templating tasks were not able to differentiate the performance of consultants, fellows, and StRs, specific aspects of the skin marking, and component orientation tasks were. Some of the key features in these simulated tasks which are associated with StRs performance, include the use of a longer skin incision for a posterior approach to the hip, and placing acetabular cups in reduced OA and increased OI in comparison to fellows and consultants.

Participant recruitment into study B allowed adequate statistical power to detect a 20% difference in MCQ scores and acetabular cup orientation between StR groups. Retention of participants and completion of follow-up assessments was also high (94%, n=32), which adds strength to the findings reported. Across the 34 StR participants, only 38% (n=13) reported that they believe the training program will meet their requirements for future clinical practice. This highlights the continued need to develop, refine, and optimise orthopaedic training programmes from a trainee perspective. Although the groups were relatively well-balanced regards the participant gender, year in training, arthroplasty placements completed/planned, and logbook numbers, a significantly greater proportion of participants within the intervention group expressed an interest in pursuing a career in arthroplasty (72%, n=13/18 versus 31%, n=5/16). At the baseline and follow-up assessments no significant differences were observed between participant groups in the MCQ score or pass rate; the templated femoral or acetabular cup component sizes; the length or curvature of skin incisions for the simulated posterior or Hardinge surgical approaches to the hip; the FSV or the overall OI and OA across all hip simulator models. However, a greater but non-significant percentage of participants from the StR intervention group achieved a passing score in the follow-up assessment in comparison to control group participants (44.4% versus 31.2%, respectively). This finding in conjunction with an observed doubling in the pass rate of StR participants from the intervention group from 22.2% at baseline to 44.4% at follow-up assessment, suggest a trend for improved knowledge acquisition in THR following simulation training. The target FSV, OI, and OA set in this study was 15°, 40°, and 20°, respectively. The median FSV/OI/OA observed across both StR participant groups, and all models used in this study was 10.7°/41.4°/24.3° at the baseline assessment, and 12.5°/39.9°/24.2° at the follow-up assessment, respectively. These readings are within 5° of the targets, which suggests that StRs are accurate in achieving a target component orientation in a simulated model. The acetabular cup orientation readings achieved by StRs in this study are also comparably better than what has been reported in other simulation-based studies, suggesting a higher baseline level of technical skills performance. (66, 78, 92, 236) No published scientific article has investigated or reported on the ability of orthopaedic surgeons or surgical trainees to achieve a desired femoral stem version in a simulated setting, and this is a novel finding. At the baseline assessment only two significant

differences were observed between groups in acetabular cup orientation angles specifically when using the tilted pelvis model with simulated soft tissues. In this model, the intervention group demonstrated significantly lower OA readings without the MAG, and lower OI readings with the MAG. The only significant difference observed between groups in their categorical proximity to the target in acetabular cup component orientation was again when using the tilted hemipelvis model with simulated soft tissues and without the MAG. Using this model, 78% (n=14/18) of participants in the intervention group were within 5° of the target OA in comparison to 25% (n=4/16) of participants in the control group. At the follow-up assessment only one significant difference was observed between the groups in acetabular cup orientation angles specifically when using the level pelvis model without simulated soft tissues and with a MAG. In this model the control group demonstrated significantly higher OI readings than the intervention group. There were no significant differences observed between groups in their categorical proximity to the target orientation in the femur or acetabular cup orientation tasks at the follow-up assessment. The only templating parameter noted to significantly improve following simulation training in comparison to consultant performance was the uncemented stem size, which went from 9/18 (50%) at baseline to 15/18 (83%) at follow-up assessment. No significant changes were observed in either the length or curvature of skin incisions for the simulated posterior or Hardinge surgical approaches to the hip. Although no significant differences in FSV were found between the baseline and follow-up assessments in participants from the intervention group, 58.3% (n=7/12) achieved FSV within 5° of the target at baseline, which increased to 91.7% (n=11/12) at follow-up assessments. Regards acetabular cup orientation, an overall decreased OI and increased OA trend was observed in participants from the intervention group from baseline to follow-up assessments, which are closer to consultant level performance metrics. However, no significant differences were found in the median OI or OA between assessments. Only two significant differences were observed between the baseline and follow-up component orientation assessments in this group, namely: a significantly reduced OI when using the level hemi-pelvis model and MAG (median 43.0° at baseline to 39.8° at follow-up), and a significantly increased OA when using the tilted hemi-pelvis model without the MAG (median 20.8° at baseline to 25.2° at follow-up). There were no significant differences observed within this group

between the baseline and follow-up assessments in the participants categorical proximity to the target orientation for the femur or acetabular cup orientation tasks.

The linked studies in study chapter eight aimed to determine the technical skills performance metrics of surgeons during primary elective THR, and both patient and institutional outcome metrics following this operation. Participant recruitment into both studies was sufficient to statistically detect a minimum 15% difference in the primary outcome metric (operative time) between surgeon groups based upon their level of experience, or StR group. The demographics of the patient participants in these studies are representative of patients undergoing primary THR across the UK. (98) Several validated novel surgeon-specific outcome metrics were used to assess and report upon the intra-operative performance of surgeons. These metrics not only included simple movement counts, but also the magnitude of linear acceleration (MLA), and the number and MLA of mallet blows during both uncemented acetabular cup implantation and femoral broaching. Another novel aspect of this research was the segmentation of a primary THR operation into discrete steps in response to the findings of the expert consensus reported in study chapter four. This allowed performance metrics of surgeons across three distinct levels of experience (consultants, fellows, and StRs) to be determined and any significant differences identified for the operation overall and within each finite steps. This exploratory research currently represents the most detailed analysis of surgeon level performance metrics in primary THR in published literature. Established and validated methodology was used to determine patient-specific and institutional outcome metrics following primary THR. This robust dataset provides a comprehensive overview of both surgeon performance and patient outcome metrics following primary THR and increases the strength of any associations reported between the two.

The construct validation study (study A) in chapter eight identified several differences in the intra-operative technical skills performance metrics between surgeon groups in relation to their level of experience during primary elective THR. Stepwise and significant differences were observed in the overall mean operative times and movement counts between consultants, fellows, and StRs, with

non-stepwise but significant differences observed in MLA. Trainees (StRs and fellows) were significantly slower and performed more movements than consultants in most steps of the operation (n=12/16 for both operative times and movement counts). The surgical approach, hip dislocation, femoral neck osteotomy, acetabular exposure, reaming and cup implantation, and femoral cementing steps demonstrated significant differences in these metrics between both StRs and fellows in comparison to consultants. Fellows demonstrated significantly increased median mallet blow MLA in comparison to consultants during acetabular cup implantation, but no significant differences were observed between surgeon groups in the number of mallet blows administered. Fellows also demonstrated significantly increased median MLA and mean number of mallet blows in comparison to consultants during femoral broaching, However, no significant differences were observed between consultants and StRs in either metric during femoral broaching. These findings suggest that mallet blow count and MLA can discriminate between fellows and consultants, but not between consultants and StRs. No significant differences were observed in the mean pre-op, post-op, or peri-operative change in OHS, EQ-5D 5L VAS, haemoglobin levels, OTBL, or any of the post-operative radiographic parameters studied in relation to surgeon group. These findings do not support the use of either PROM, surrogate markers of blood loss, or post-operative radiographic parameters for discriminating between surgeons performance based upon their level of experience. Patients undergoing consultant-led operations were observed to have significantly shorter mean LOS in comparison to fellows, but not StRs, and no significant differences were observed in the incidence of all cause re-admissions to hospital, or re-operations within 30 days of the index operation in relation to surgeon grade.

The randomised controlled pilot study (study B) in chapter eight aimed to assess the impact of several independent surgeon variables on the intra-operative performance metrics of StRs and patient outcomes following supervised StR performed primary THR. Although the primary independent variable investigated was the impact of the simulation training module, the number of years of specialty training experience (PGY); number of primary THR performed as first surgeon (STS-THR); and PBA level achieved for each case were assessed as secondary variables. The results did

not identify any significant differences in either the mean total operative time or movement counts to perform a primary elective THR in relation to the StR group (simulation training or control groups). Although this suggests that additional simulation training did not result in any significant improvement in intra-operative performance metrics in this cohort of StRs, it must be noted that this was a pilot study involving a relatively small cohort of seven StRs with a heterogenous spread in training experience (grade and number of STS-THR performed). Only two out of the seven StR participants in this study were ST3/4 level, with one randomised into the intervention and one in the control group. This potentially limits the impact of additional simulation training on the intra-operative performance metrics studied at a group level as early-stage trainees inevitably benefit more from additional training than those in the final stages of their training whose operative skills and experience are more advanced. This is supported by the finding of significant reductions in both mean total operative time and movement counts with increasing StR PGY, and PBA level. This demonstrates that more experienced trainees demonstrate improved intra-operative performance metrics with concomitant improvements in PBA level. The specific steps associated with significant reductions in both operative times and movement counts in relation to StR PGY and PBA level included the surgical approach, acetabular reaming, femoral broaching, and initial head trialling. Regards acetabular cup implantation, significant differences in the mean number of mallet blows were observed in relation to the StR group, PGY, and the number of STS-THR, with significant differences also observed in the median MLA of mallet blows in relation to StR PBA level only. Regards femoral broaching, significant differences in the mean number of mallet blows were observed in relation to PBA level alone, with no differences observed in the median MLA of mallet blows in relation to StR group, PGY, number of STS-THR performed, or PBA level. The lack of construct validity in PROMS, surrogate markers of blood loss, and post-operative radiographic parameters outlined in chapter eight study A limits any interpretation of differences identified in study B. Furthermore, no significant differences were observed in the mean LOS in relation to StR group, PGY, number of STS-THR performed, or PBA level.

In summary, the overall operative time, movement count, and MLA are validated metrics for differentiating the intra-operative performance surgeons in THR based upon their level of experience. The most significant differences in overall intra-operative performance metrics between consultants and StRs were the total movement count, followed by the operative time, and median right- and left-hand MLA. The main differences in performance metrics between trainees and consultants were observed within the surgical approach, hip dislocation, femoral neck osteotomy, acetabular exposure, reaming and cup implantation, and femoral cementing steps of this operation. These findings are in keeping with the results of the expert consensus in chapter four, which found that acetabular reaming, exposure, and cup orientation were the most critical steps for optimising patient outcomes and difficult to teach trainees. Furthermore, the surgical approach was judged to be the single most critical step for patient outcome (94% agreement), but also easy to teach trainees (84% agreement). However, significant differences between consultants and StRs were observed in at least one performance metric for every step of the operation. The use of PROMs, post-operative radiographic metrics, and surrogate markers of blood loss are not sensitive enough to differentiate between surgeons based upon their level of experience. Post-operative patient length of stay (LOS) was the only institutional outcome metric observed to demonstrate a significant difference between surgeon groups, with a lower mean LOS observed in consultant led primary THR (2.4 days) in comparison to fellows (3.6 days), but not StRs (3.2 days). Although the impact of simulation training on surgeon-specific performance metrics in this study was limited, further larger scale studies are required to investigate this in greater detail and determine the optimal stage for delivery of this training.

The objective metrics developed and evaluated within these studies may potentially be used by trainers as surrogate markers of trainee performance within the domain of surgical skills assessment, and to help guide the personal development of trainees by identifying specific steps of the operation which require improvement. The findings of this research support the use of PBAs for identifying optimal trainee surgeon performance metrics in primary elective THR. Furthermore, the importance of an StRs operative and clinical experience as reflected in the total number of STS-THR achieved

and PGY has been highlighted, with direct positive correlations observed between higher performance metrics and increased categorical number of STS-THR and PGY. The focussed and evidence-based surgical simulation training module developed for use in this research was clearly well received by trainees, as reflected in the positive feedback. However, the findings of this research do not demonstrate a clear positive impact of this simulation training module on the objective metrics of surgical technical skills performance in a small cohort of orthopaedic trainees during primary elective THR. Future research may use the novel metrics and methodology established in this thesis to investigate the impact of alternative simulation training modalities, models, or duration of training on surgical performance or patient outcome metrics following THR, or any other commonly performed operation. Validating the transferability and impact of skills acquired using simulation training is perhaps the single most important step for justifying their incorporation into surgical training. Further research and development in this field may hopefully identify and validate cost-effective and user-friendly simulation training modalities which may be used to augment the traditional apprentice style model of training in orthopaedic surgery. Ultimately, increasing numbers of trainee-led operations (STS-THR) and PGY are the only factors which have been associated with improved performance metrics in primary THR. This finding suggests that simulation training cannot substitute for a reduced volume of practical operative and clinical experience during orthopaedic training. Organisations and individuals responsible for delivering surgical training should use the results of this research to maximise the operative experience of trainees during clinical placements, ensure adequate intra-operative supervision is in place, and consider the integration of novel objective metrics for assessing trainee performance, competence, and progression through a training program.

9.2 Future work

Future research may focus upon refining the signal processing techniques of the data acquired from inertial sensors and investigate the magnitude of force generated by surgeons when striking a hammer to impact acetabular cups or cementless femoral stems. This may help surgeons and researchers to better understand the optimal forces and frequency of application required to safely and satisfactorily impact uncemented implants when performing primary THR. A recent study using a drop rig set up and synthetic simulated bone models in a laboratory environment has highlighted the importance of the force used for impacting cementless acetabular cups. (345) Inertial sensors may be used to collect accelerometery data, and the mass of the surgical hammer is known, so theoretically it may be possible to calculate the force generated using the principles of Newtons second law. Practically this would be difficult however, as the acceleration of the hammer at the point of impact and both the weight and length of the persons arm would both have to be accounted for. Further laboratory studies controlling these variables may advance our understanding of the optimal force required to strike surgical tools such as femoral rasps and impact uncemented orthopaedic implants. This research has established thresholds in MLA from elbow inertial sensors which correlate with intra-operative hammer strikes. For the purposes of this research each peak in MLA above this threshold was counted, but not quantified. Theoretically, custom scripts could enable each of these peaks to be quantified along with details on the time span between peaks. This information would provide an insight into the magnitude and frequency of hammer strikes for each surgeon. This information would not only be interesting to study from a construct validation perspective (identifying any differences between surgeons of differing levels of experience), but it would also allow surgeons to gain a better insight into their impaction technique and potential ways to improve upon this. This information may be linked to potential intra-operative complications such as femoral or acetabular fracture when impacting prostheses. This may lead to a better understanding of the maximum recommended MLA allowed to avoid such complications. Real-time intra-operative feedback systems for displaying MLA may also be developed to forewarn surgeons that their hammer swings are too forceful and at risk of causing iatrogenic complications.

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Appendices

A. General Appendix for Study Chapter 4

A.1 Invitation to participate in Expert Consensus and Round 2 Questionnaire

Expert Consensus (Delphi Analysis) on Performance & Training in Primary Total Hip Replacement (THR)

Dear Colleague,

This questionnaire forms part of a PhD project focused on establishing new strategies to improve surgical training in primary THR. We aim to provide improvements and guidance on the best methods for trainees to accelerate their learning at THR and ways in which Trainers can further facilitate this process.

This short two-page survey is part of a Delphi consensus process aimed at defining the key stages and steps of THR surgery. The results of this analysis will provide information to guide specific training interventions to improve learning during particular stages of this operation.

An assessment of agreement between trainers about the critical stages has not been previously undertaken and your input and help in completing this short survey and your willingness to be contacted in the future to complete a follow up survey would be greatly appreciated.

If you are content to be contacted in the future, please provide your contact details and we will presume your permission to follow-up via e-mail, post, or telephone as you indicate. You may withdraw your consent at any time-point. Your contact details will remain confidential and your responses anonymous. Upon completion all participants will be informed of the results of this Delphi analysis.

This project has the support of the BHS Executive and the BOA Training and Standards Committee. Many thanks for participating in this Research project which we hope will have a national impact.

Your sincerely,

Daniel Howgate
MBChB BSc (Hons) FRCS (Tr&Orth)
Specialty Registrar and Research Fellow
Oxford Deanery

Ben Kendrick
MB BS DPhil (Oxon) FRCS (Tr&Orth)
Consultant Orthopaedic Surgeon
Nuffield Orthopaedic Centre, Oxford

Inclusion criteria for participation

- Consultant Orthopaedic Hip Surgeons currently practicing within the NHS with a specialty interest and clinical practice in Hip Arthroplasty
- An active or recent (<5 years ago) role in Teaching & Training Specialty Registrars or Fellows

Your Details – Please include your contact details if you would be happy to receive a follow-up questionnaire

Title	Professor / Mr / Miss / Dr / Other
Name	
E-mail	
Address	
Telephone	

Preferred contact method (please tick): E-mail ☐ Postal Letter ☐ Telephone ☐

Clinical Practice

Please circle **one** option for each question:

1	Do you currently train Registrars and/or Fellows in Primary Hip Arthroplasty?	YES	NO
2	Have you trained Registrars and/or Fellows in Primary Hip Arthroplasty in the last 5 years?	YES	NO
3	Are you a designated Clinical Supervisor or Assigned Educational Supervisor?	YES	NO

On average how many THR do you perform each year? (Please tick **one** option for each)

	<10	10-20	20-30	30-40	40-50	50-100	100-200	200-300	300+
Primary									
Revision									

Number of years of Consultant practise
(Please tick **one** option)

<5	5-10	10-15	15-20	>20

Hospital setting
(Please tick **one** option)

University Teaching Hospital	
District General Hospital	

Preferred pre-operative planning, patient positioning, and approach for Primary THR
(Please tick **one** option for each)

1. Pre-op Templating	Digital		Manual		None	
2. Patient Positioning	Lateral		Supine			
3. Surgical Approach	Posterior		Hardinge (Lateral)		DAA	

	How much impact do you feel the following steps have on the *outcome* of the operation? (Please tick **one** option)			Whether you find it easy *to teach* this step to your trainees? (Please tick **one** option)	
	Little	**Moderate**	**Substantial**	**Yes**	**No**
Pre-op Templating					
Patient Positioning					
Skin preparation and draping					
Skin Incision & Surgical Approach					
Acetabular Preparation					
Acetabular Exposure					
Labral resection/Osteophytectomy					
Acetabular Reaming					
Implant Sizing & Trialling (including trimming of cemented cup if using)					
Acetabular Component Implantation					
Anteversion					
Inclination					
Depth (e.g. medialising to floor)					
Femoral Preparation					
Femoral Exposure					
Femoral neck osteotomy					
Femoral canal					
Implant Sizing & Trialling					
Femoral Component Implantation					
Version					
Varus/Valgus alignment					
Cementing (if applicable)					
Cement mixing & handling					
Acetabular drill holes					
Acetabular lavage & packing					
Acetabular cement insertion & pressurisation					
Femoral canal cement restrictor sizing					
Femoral canal lavage, suction & packing					
Femoral cement insertion & pressurisation					
Intra-Operative Assessment & Restoration of Hip Anatomy					
Assessing & accurately reconstructing Leg length					
Assessing & accurately reconstructing Hip offset					

Any other critical steps not listed above?.....

Preferred Fixation Method for Primary THR
(Please circle **one** option)

Fixation	All Cemented	Hybrid	All Uncemented	Reverse Hybrid

Please hand in completed forms to the reception desk or the collection box at exit. Many Thanks.

B. General Appendix for Study Chapter 5

B.1 Delegate workbook for simulation training module

NDORMS
NUFFIELD DEPARTMENT OF ORTHOPAEDICS, RHEUMATOLOGY AND MUSCULOSKELETAL SCIENCES
Medical Sciences Division

UNIVERSITY OF OXFORD

Oxford Surgical Simulation Course for Primary Total Hip Replacement



Delegate Workbook

Funded & endorsed by

Royal College of Surgeons
ADVANCING SURGICAL CARE

DINWOODIE
CHARITABLE COMPANY

British Orthopaedic Association

Supported by

Corin
Connected Orthopaedic Insight

stryker

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Introduction

Welcome to the Oxford Total Hip Replacement Surgical Simulation Course.

This course has been designed specifically for Trauma & Orthopaedic Surgical Trainees with the primary aims of:

1) Enhancing participants knowledge of the basic scientific principles which underpin a successful THR.
2) Learning how to perform the key steps of a THR, which are critical to patient outcomes.
3) Practising and optimising your surgical skills in THR using a range of simulated models and techniques under supervision in the safety of a non-clinical environment.
4) Highlighting any areas for personal improvement, through the use of formative assessments.

The course uses a combination of didactic lectures to deliver all the requisite scientific knowledge, and practical skills sessions using a range of simulation models in order to allow delegates hands on experience of the equipment and techniques used in primary THR. The content of these sessions has been formulated specifically in response to an expert consensus on the key steps of a primary THR, which has highlighted the steps which are either critical to patient outcomes, or particularly difficult to teach 'on the job'.

At the start and end of this course we will ask you to complete a short 20 question Multiple Choice Questionnaire (MCQ) and undertake a practical skills assessment in the simulation laboratory. We will also request your written informed consent to gather information about your training history, surgical e-logbook data, and relevant surgical courses attending as part of your training to date.

Constructive feedback is encouraged following this course, which will be used to improve the quality, relevance, and delivery of this training programme for future surgical trainees.

Following completion of this course we will be following a small number of T&O Specialty Registrars throughout their 6-month clinical placements on Adult Arthroplasty in order to assess the impact of this training on both their intra-operative performance, and their patients' outcomes following THR.

We hope that you enjoy participating in this course.

Mr Daniel Howgate
MBChB BSc (Hons) FRCS (Tr&Orth)
Specialty Registrar and Research Fellow
Oxford Deanery

Mr Ben Kendrick
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Course Overview

Session	Time
Introduction, participant consent, and training history forms	**8:30am – 9am**
ASSESSMENT 1) Baseline MCQ & Templating exercise 2) Practical skills assessment: skin incision & component positioning	**9am – 10am**
LECTURE Principles of THR, templating, patient set-up, and surgical approaches	**10am – 10:30am**
Coffee Break	**10:30 – 11am**
LECTURE Acetabular preparation, and component implantation	**11am – 11:30am**
PRACTICAL Acetabular preparation, and cemented/uncemented component implantation	**11:30am – 12:30pm**
Lunch Break	**12:30 -1pm**
LECTURE Femoral preparation, and component implantation	**1pm – 1:30pm**
PRACTICAL Femoral preparation, and cemented/uncemented component implantation	**1:30pm – 2:30pm**
LECTURE Reconstructing hip anatomy and biomechanics.	**2:30pm – 3pm**
Course summary, questions, & close	**3pm – 3:15pm**

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Principles of THR, templating, patient set-up & surgical approach

Surgical steps of a Total Hip Replacement

The following table outlines the key steps and skills required in order to perform a primary THR. This has been established using a combination of surgical literature, current recommendations from the T&O Specialty Advisory Committee (SAC), and expert opinion.

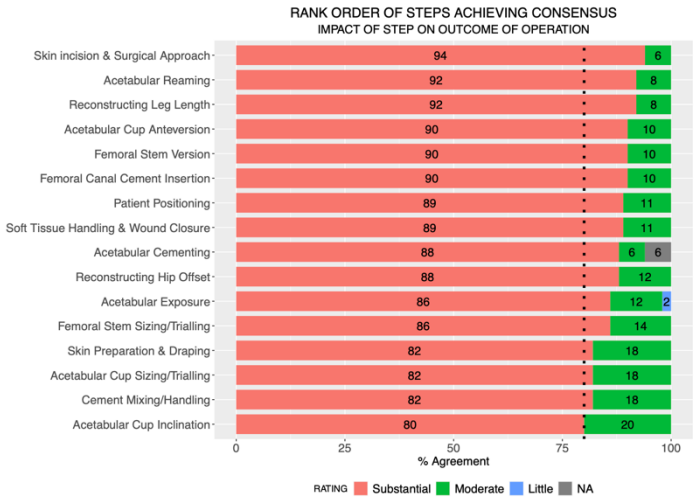
Pre-op planning, Patient Positioning & Surgical Approach
Pre-op Templating
Patient Positioning
Skin preparation and draping
Skin Incision & Surgical Approach
Acetabular Preparation
Acetabular Exposure
Labral resection/Osteophytectomy
Acetabular Reaming
Implant Sizing & Trialing (including trimming of cemented cup if using)
Acetabular Component Implantation
Anteversion
Inclination
Depth (e.g. medialising to floor)
Femoral Preparation
Femoral Exposure
Femoral neck osteotomy
Femoral canal preparation/broaching
Implant Sizing & Trialing
Femoral Component Implantation
Version
Varus/Valgus alignment
Cementing (if applicable)
Cement mixing & handling
Acetabular drill holes
Acetabular lavage & packing
Acetabular cement insertion & pressurisation
Femoral canal cement restrictor sizing
Femoral canal lavage, suction & packing
Femoral cement insertion & pressurisation
Intra-Operative Assessment & Restoration of Hip Anatomy
Assessing & accurately reconstructing Leg length
Assessing & accurately reconstructing Hip offset
Closure
Soft tissue repair & wound closure

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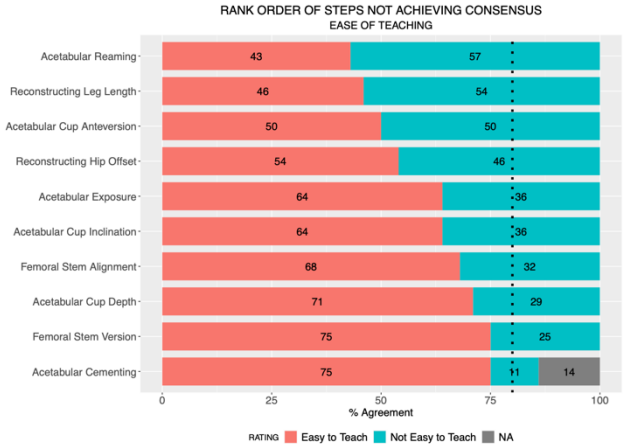
Delphi Analysis (Expert Consensus) on steps of a Total Hip Replacement

In March 2019, a questionnaire was distributed to 50 Consultant Orthopaedic Surgeons at the Annual Scientific meeting of the British Hip Society (BHS). This questionnaire was aimed at defining the key stages and steps of THR surgery. Participants were asked to rate the importance of each step of a primary THR in terms of its impact on the ***outcome*** of the operation, and whether they find it easy ***to teach*** to orthopaedic trainees. The results of this Delphi analysis have highlighted the following key steps identified as the most critical in terms of patient outcomes following THR, or the most difficult to teach trainees. We have used these results to focus both the cognitive and simulation training aspects of this course.

Stacked bar plot showing the rank-order of steps achieving consensus for importance on the **outcome** of the operation (dashed line indicates 80% consensus threshold).



Stacked bar plot showing the rank-order of steps not achieving consensus for **ease of teaching** surgical trainees (dashed line indicates 80% consensus threshold).



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Basic biomechanics of the hip, and principles of THR

The hip joint, or acetabulofemoral joint, is a complex multi-axial di-arthrodial synovial ball-and-socket joint. The acetabulum forms the socket, which itself is formed at the confluence of all 3 bones of pelvis (ilium, pubis, and ischium), and the femoral head forms the ball. The surgical anatomy of the hip joint will be covered in greater detail in the approaches section. The primary function of the hip joint is to support and transfer the weight of the body onto the leg/s in both static (standing) and dynamic (walking or running) postures. The hip has a large range of movement in all 3 planes:

- Flexion 130º/Extension 10º in the sagittal (Y) plane
- Abduction 40º/Adduction 30º in the coronal (X) plane
- Internal & external rotation to 40º (tested in hip flexion & extension) in the axial (Z) plane

The native hip joint is inherently stable. Its stability is derived from a combination of the congruency of its bony structure, and both static (acetabular labrum, ligaments and capsule) and dynamic stabilisers (hip musculature). The stability of a THR is compromised by iatrogenic disruption of both the static and dynamic stabilisers of the hip during the surgical approach, and also a smaller prosthetic head/cup articulation. The hip experiences enormous physiological forces, with up to 3 times body weight passing through the joint during normal walking, and up to 7 times body weight in fast walking [1]. Free body diagrams are static 2-dimensional representations of joints that may be used to calculate the forces across a joint, such as the hip Please see appendices for an example of a free-body diagram of the hip joint. In osteoarthritis (OA), increased friction across the damaged joint surface requires the patient to generate a greater abductor force. In order to reduce the Joint Reaction Force (JRF) across the hip a number of strategies may be employed [1], including:

- Reducing body weight
- Medialise the axis of rotation by leaning towards the affected hip (Trendelenburg gait)
- Provide additional counter moments (walking stick in contralateral hand, or bag in ipsilateral hand)
- Increase the abductor lever arm/femoral offset surgically, by:
    - Lateralising femoral offset in THR.
    - Varus osteotomy to decrease neck-shaft angle.
    - Medialise the hip centre of rotation (e.g. medialised cup placement), whilst increasing femoral offset.
    - Trochanteric osteotomy with distalisation and lateralisation.

Restoration of normal hip biomechanics during THR is known to result in: improved patient function & satisfaction; reduced incidence in complications such as dislocation; and significantly increase the longevity of the implants [2-7]. The surgical anatomy of the hip joint, and parameters for biomechanical restoration during THR will be covered in greater detail during the surgical approach and pre-operative templating sections of this workbook, but in general the following parameters of hip biomechanics must be considered pre-operatively and recreated intra-operatively in order to produce a satisfactory result for the patient following THR:

- Centre of rotation (COR) of the hip joint
- Femoral offset (FO) and acetabular offset (AO)
- Femoral neck version and neck-shaft angle (NSA)
- Acetabular orientation: inclination and version
- Leg length (LL)

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The principle aims of a THR are to:

1) Reduce pain
2) Correct deformity
3) Restore normal hip biomechanics
4) Improve range of movement

Indications & contra-indications for a primary THR

Planning for a THR starts with careful patient assessment, including a detailed history and examination. This process helps to identify factors which will influence the operation, recovery, and likelihood of a successful outcome. Patient selection for THR depends upon a variety of factors, however the common themes may be divided into:

1) Patient characteristics (age, activity, co-morbidities), and severity of symptoms or physical signs (pain or deformity).
2) Surgeon's clinical judgement and experience.

According to the 15th Annual Report of the National Joint Registry, the average age of a patient receiving a primary THR is 68.0 years old (SD 11.4), with 59.8% of patients being female, and 40.2% male [8].

Common indications for a primary elective THR are as follows:

- Primary end-stage osteoarthritis (the most common indication)
- Rheumatoid or other inflammatory forms of arthritis
- Hip fracture (acute neck of femur fracture, chronic post-traumatic OA, or pathological)
- Congenital or developmental hip dysplasia
- Avascular necrosis (AVN)
- Failed previous hip surgery (proximal femoral fixation, hemiarthroplasty)
- Previous infection or arthrodesis

Contra-indications to THR include:

- Active infection anywhere in the body, or suspected latent infection in or about the hip joint.
- Bone stock that is inadequate for support or fixation of the implants (relative contraindication, and more important to note when using uncemented implants).
- Neuro-muscular or cognitive disorders which place the patient at an unacceptably high risk of dislocation
- Skeletal immaturity.
- Allergy to implant materials.

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Implant fixation and bearings in THR, the NJR, and ODEP

Implant Fixation

The modes of implant fixation in THR are described as:

- **All cemented**: Both acetabular and femoral components cemented.
- **All uncemented**: Both acetabular and femoral components uncemented.
- **Hybrid**: Uncemented acetabular component, with cemented femoral component.
- **Reverse Hybrid**: Cemented acetabular component with uncemented femoral component.
- **Hip Resurfacing Arthroplasty**: will not be covered within this workbook.

Please see the appendix for a detailed review of bone cement.

Types of bearing

A detailed review of the bearings used for THR (material and head size) is beyond the scope of this workbook, however in principle the bearing surface options available include:

- Metal head on Polyethylene liner (MoP)
- Ceramic head on Polyethylene liner (CoP)
- Ceramic head on Ceramic liner (CoC)
- Metal head on Metal liner (MoM)
- Ceramic head on Metal liner (CoM)

The most common head sizes used in clinical practice are: 28mm, 32mm, and 36mm.

National Joint Registry (NJR) and Orthopaedic Data Evaluation Panel (ODEP)

To date, the most common type of fixation in THR is all uncemented, constituting 37.3% of all THR recorded since the inception of the National Joint Registry (NJR). All cemented component fixation constituted 31.8%, all hybrid fixation 22.0%, and reverse hybrid 2.6%. However, over time, trends have changed in the mode of fixation. Please see the appendix for a graphical representation of the temporal change in fixation modalities used in primary THR, as well as the most commonly used cemented and uncemented acetabular and femoral implants.

The operating surgeon generally chooses the implants/prostheses, taking into consideration those that achieve the recommended standard revision rate as provided by the Orthopaedic Data Evaluation Panel (ODEP). ODEP is comprised of an independent panel of experts, responsible for reviewing and rating the evidence regarding performance and longevity of orthopaedic implants. They issue a rating comprised of a number and letter for each implant registered. The number represents the number of years for which the products performance has been evidenced, and the letter represents the strength of evidence (A = strong evidence, B = acceptable evidence). NICE recommends that prostheses used for THR have rates (or projected rates) of revision of 5% or less at 10 years [9]. Please see the appendix for a pictorial representation of ODEP ratings.

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Templating in THR

The value, accuracy, and reliability of pre-operative templating is well recognised in THR [10-14]. The primary purpose of pre-operative planning and templating is to help surgeons:

1) Estimate the correct implant size (femoral stem or acetabular cup) for the patient.
2) Identify normal hip anatomy: specifically, the centre of rotation of the hip, femoral offset, and leg length.
3) Highlight any important anatomical variations or potential problems before the operation: for example, bone loss, coxa vara/coxa valga, previous operations or metalwork.

An awareness of these factors helps surgeons and theatre staff to:

1) Ensure that the appropriate size and type of implants and other special surgical equipment (for example bone graft, or augments) are requested in advance and available for use on the day of surgery.
2) Accurately reconstruct the patient's normal hip anatomy & biomechanics.
3) Anticipate and prepare for any variations in the operation.
4) Reduce the risk of intra-operative complications or deviations from planned surgical care.
5) Enhance the efficiency of the theatre team throughout the operation and the theatre list.

Templating is most commonly performed using custom digital software on scaled digital radiographs from the Picture Archiving and Communication Systems (PACS) [13]. However, it can be performed manually using manual acetate overlays of implant templates on either hard copies of radiographs against a lightbox, or by using scaled digital radiographs [15]. A 120% magnification is standard scaling for most acetate templates.

Scaling of the radiographs is critical to accurate templating

Scaling is normally achieved by placing a single radio-opaque marker ball of a fixed known diameter between the patient's thighs when they are having a pre-operative AP Pelvis radiograph. Double marker methods have also been described [16]. The maker ball should be placed in the coronal plane of the hip in order to provide suitable accuracy [17]. Scaling allows for the correction of any magnification discrepancies between the radiographs and the implant templates. Digital templating software facilitates this process as it scales the radiographs appropriately after the size of the marker ball has been marked and calibrated accordingly. The magnification of digital radiographs can also be adjusted to match acetate template overlays using PACS software.

Steps in pre-operative templating

1) Confirm the patient's identity and the position of the radiograph.
2) Assess the adequacy of the radiograph which you are templating.
3) Assess the normal native hip anatomy (centre of rotation of the hip, the femoral offset, and leg length). This can be performed using the contralateral hip joint if this is not affected.
4) Assess for any bone deficiency of excess around the affected hip joint (erosions, cysts, osteophytes).
5) Determine the implant sizes and ideal placement in order to recreate the patient's native hip anatomy.

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Step 1: Confirm the patient's identity and position of the radiograph

- Check the radiographic annotations, including: the patient details, date of the radiograph, institution it was taken in, and the presence of a side marker (which should not obscure any anatomy).
- Ideally, radiographs should be performed within 3 months of the anticipated date of surgery.
- An antero-posterior (AP) pelvis radiograph is mandatory, and a lateral hip radiograph is preferable.

Step 2: Assess the adequacy of the radiograph which you are templating.

- The AP radiograph should be centred over the mid-point between the anterior-superior iliac spine (ASIS) and the pubic symphysis.

- The entirety of the pelvis must be visible, including both iliac crests, hip joints, and the proximal third of the femurs (to below the level of the lesser trochanters). The sacroiliac joints, pubic and ischial rami should also be visible.

- Assess the rotation and tilt of the pelvis. Ideally the pelvis should appear symmetrical, which may be judged by the symmetry of the iliac crests, obturator foramens and pelvic inlet, with the coccyx being in line with the pubic symphysis, with the tip being located approximately 3cm above it.

- Both femurs should be internally rotated by 15-20° whilst taking a pelvis AP radiograph, which provides a true AP of the femoral necks, and allows accurate estimation of femoral offset (see figure 1).
    - The prominence of the lesser trochanters (LT's)provides an indication of femoral rotation.
    - More prominent LT's indicate that the femur is externally rotated. Externally rotated femurs will falsely increase the femoral neck-shaft angle (NSA), and reduce the femoral offset (FO).
    - If the LT's are not visible then the femurs are excessively internally rotated.

- Inadequate patient radiographs may carry significant patient safety and financial implications [18].

- Pre-op planning on a mal-rotated or otherwise inadequate radiograph will lead to an inaccurate pre-operative plan.

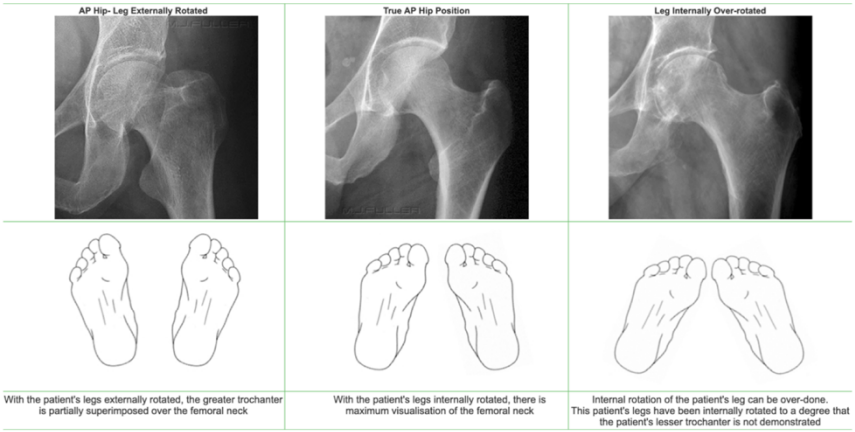


Figure 1: The effect of femoral rotation on the view of the femoral neck.

The femurs should be internally rotated by 15-20°

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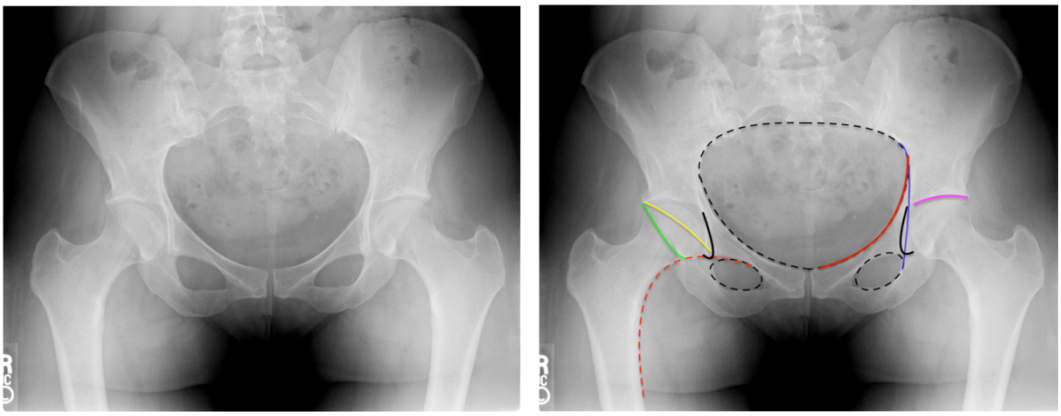


Figure 2: a) Normal AP pelvis radiograph b) Marking with anatomical marking lines

Line	Anatomical Structure		Line	Anatomical Structure
Dashed black	Pelvic ring (superior) and obturator rings (inferior)		Dashed Red	Shenton's line
Solid Red	Iliopectineal line (Anterior column)		Solid Pink	Acetabular roof / Sourcil
Solid Purple	Ilioischial line / Köhlers line (Posterior column)		Solid Green	Posterior acetabular wall
Solid Black	Acetabular teardrops (End-on projection of a bony ridge running along the floor of the acetabular fossa)		Solid Yellow	Anterior acetabular wall

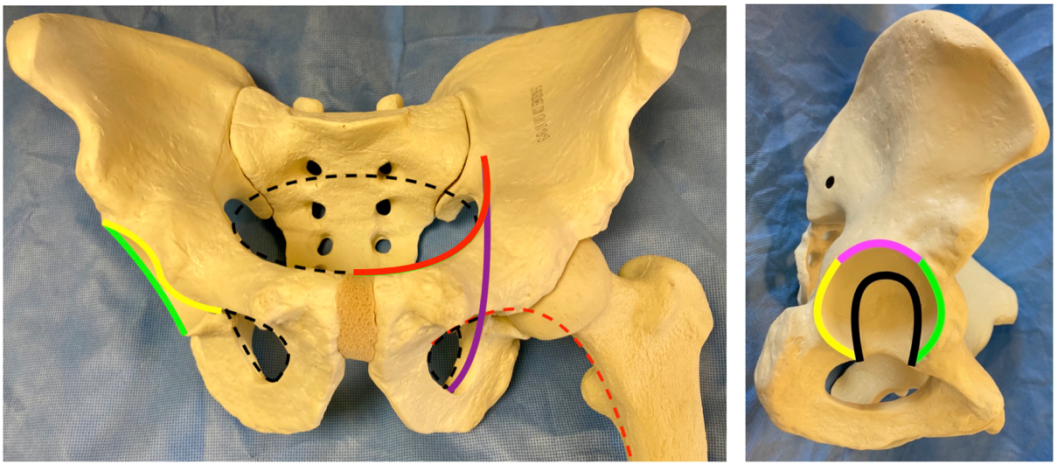


Figure 3: a) AP Pelvis Sawbone® b) Left hemi-pelvis Sawbone® with anatomical marking lines

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Step 3: Assess the 'normal' hip anatomy.

The centre of rotation (COR) of the hip, femoral offset (FO), and leg lengths (LL) should be assessed on the 'normal' side and templating performed in order to restore these on the planned operative side.

Centre of rotation of the hip

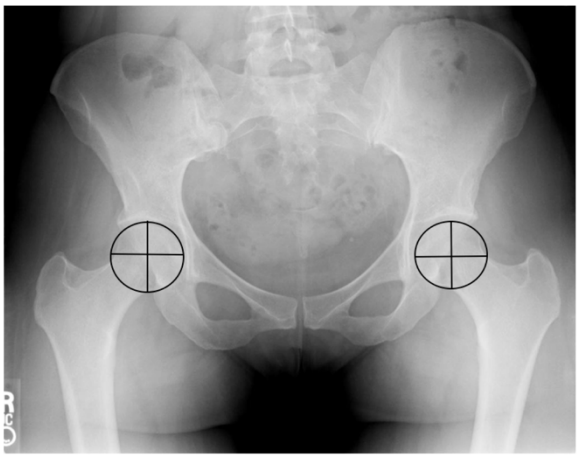


Figure 4: Normal AP pelvic radiograph

Hip Centre of Rotation (COR) represented by centre of cross-hairs within the femoral head

Femoral offset

Femoral offset (FO) is defined as the perpendicular distance between the centre of the femoral head and a line drawn down the shaft of the femur (anatomical axis) [3, 19]. Acetabular offset (AO) is defined as the perpendicular distance from the COR of the hip to the vertical trans-teardrop line [6]. The combined offset (CO) or global offset, is the combined FO and AO.

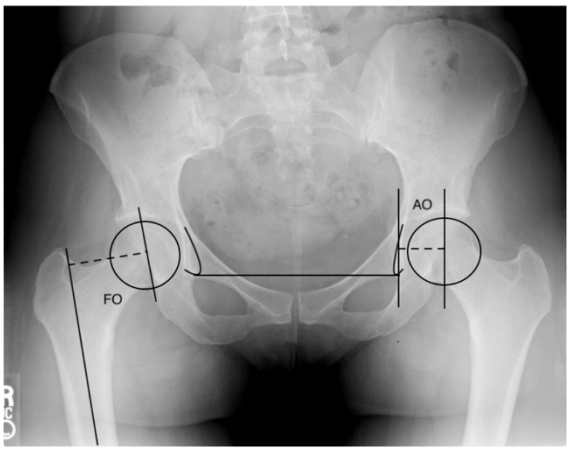


Figure 5: Normal AP pelvic radiograph

FO = Femoral offset AO = Acetabular offset

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FO is affected by a number of other anatomical factors, namely:

1) The femoral neck-shaft angle (NSA)
2) The femoral neck anteversion

The **femoral neck-shaft angle** (NSA) is assessed in the coronal plane.

- A varus NSA (Coxa Vara) increases the FO
- A valgus NSA (Coxa Valga) decreases the FO

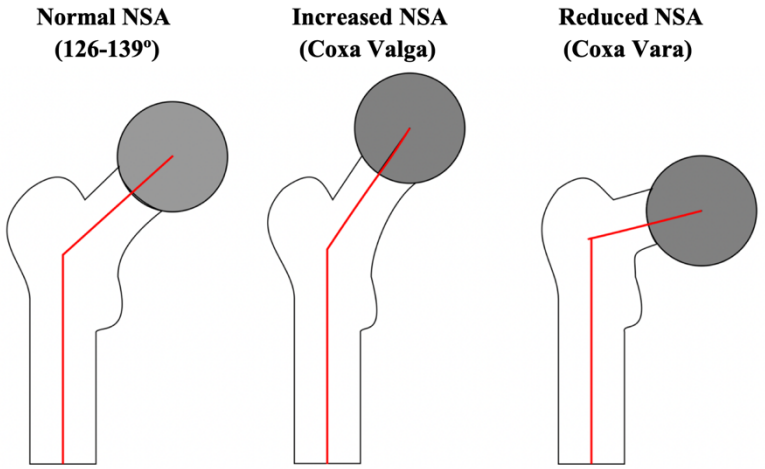


Figure 6: Femoral neck-shaft angles (NSA)

The mean native NSA is 130°+/-5°, and a decrease in FO is often due to a femoral stem NSA which is greater than the native NSA [20]. NSA vary with implants and manufacturers, and it is important to know the NSA and options available on the implant system that you will be using.

The **femoral neck anteversion**, which is assessed in the axial plane is referenced off the posterior bicondylar line of the distal femur (see figure 7):

- Increased femoral anteversion decreases the FO [21]. Internal rotation of the femur 15-20° whilst taking a pelvis AP radiograph mitigates for this distortion.

- Femoral anteversion cannot be accurately assessed clinically or by using an AP pelvis radiograph, and therefore a CT scan should be considered the gold standard of further investigation if a significant degree of femoral anteversion this is clinically suspected pre-operatively.

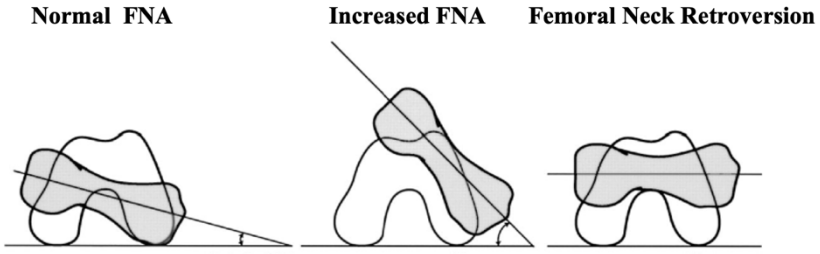


Figure 7: Proximal femoral version demonstrated in axial view of right femur

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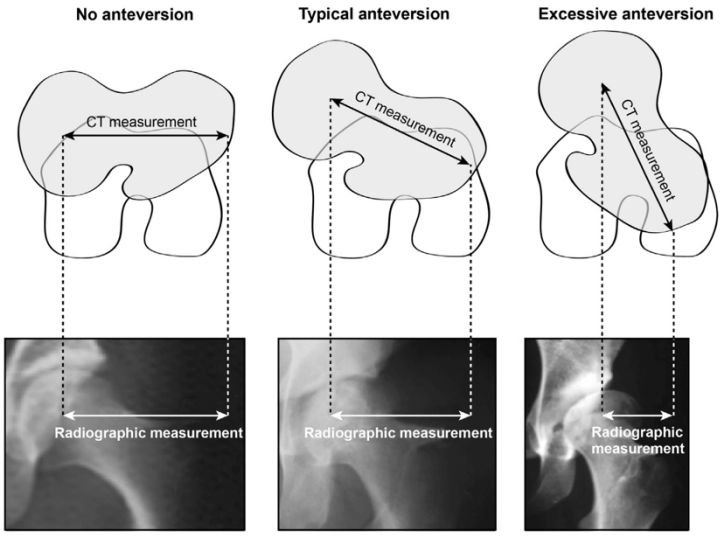


Figure 8: The effect of femoral version on the measurement of femoral offset using CT and plain radiographs [6]

Leg length

Fixed anatomical points on both the pelvis and proximal femurs are used to assess and template anatomical leg lengths radiographically [22, 23].

a. The acetabular tear-drops or ischial tuberosities are commonly used as bony landmarks in the adult pelvis [24].
b. The lesser trochanters or centre of the femoral heads are commonly used as bony landmarks in the adult femur.

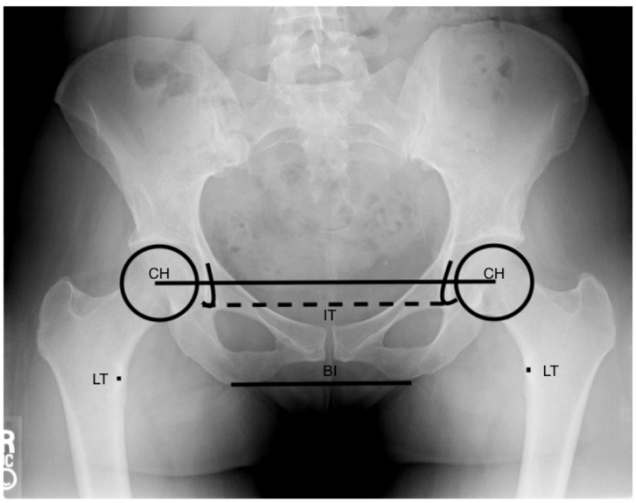


Figure 9: Commonly used anatomical landmarks for measuring leg lengths

CH = Centre of Femoral Head (dashed black line)
IT = inter-teardrop line (solid black line)
LT = lesser trochanter
BI = Bi-ischial (or inter-ischial tuberosity) line

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Meermans *et al* validated the different methods for pre-operative radiographic measurement of LLD and evaluated their reliability [22]. They reported that the inter- and intra-observer agreement is greatest when using:

1. The inter-teardrop line for the pelvis (solid black line in figure below).
2. The centre of the femoral head for the femurs (dashed black line in figure below).

Another study has reported that measuring leg lengths from the inter-ischial tuberosity line to the most prominent medial point on the lesser trochanter appears to be the best method for measuring LLD [25].

In practice, a combination of the above techniques may be beneficial. The centre of femoral head (CFH) to acetabular teardrop (TD) to lesser trochanter (LT), or CFH-TD-LT method is one such method which can comprehensively assess both the pelvic and femoral components of leg length discrepancy [26].

In the figure 10 the inter-tear-drop line is used as the pelvic reference point, which can be connected by drawing a line either digitally or manually. A perpendicular vertical distance between this line and the centre of each femoral head can then be measured in order to objectively quantify any anatomical leg length discrepancy. Any significant LLD must be accounted for and an attempt made to equalise this difference intra-operatively.

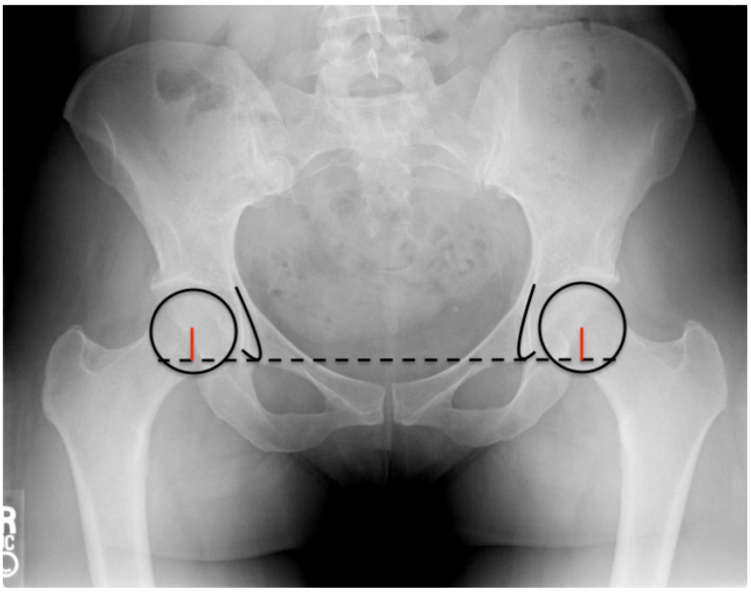


Figure 10:

Normal AP pelvic radiograph with inter-teardrop line (dashed black) and distance to the centre of the femoral head marked in red

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Step 4: Assess for any bone deficiency or excess around the affected hip joint

The radiographic hallmark of osteoarthritis (OA) is joint space narrowing. Most commonly, this narrowing is associated with subchondral sclerosis, marginal osteophytes, cyst formation, and superolateral subluxation of the femoral head (seen in Figures 11 and 12) [27].

OA has been classified as atrophic, normotrophic, hypertrophic, or rapidly destructive [28, 29]. Atrophic OA is characterised by widespread cartilage loss with joint space narrowing and superolateral subluxation of the femoral head, but with little bone response and minimal osteophyte formation [30, 31]. The atrophic form of OA has been described mostly in elderly females, with radiologic evidence of hip dysplasia (narrow centre-edge angles and poor femoral head coverage). Normotrophic OA describes the equilibrium between bone destruction and regeneration that is observed in the majority of OA hips. Hypertrophic OA shows localised cartilage loss and florid bone formation in the form of osteophytes. Patients with hypertrophic OA and marked osteophytosis may be more susceptible to post-operative heterotopic ossification (HO) around the hip, and consideration should be given to medical prophylaxis, such as the administration of peri-operative indomethacin if no contra-indications exist. The term destructive OA applies to cases with rapid destruction of bone and cartilage from the femoral head and the acetabulum.

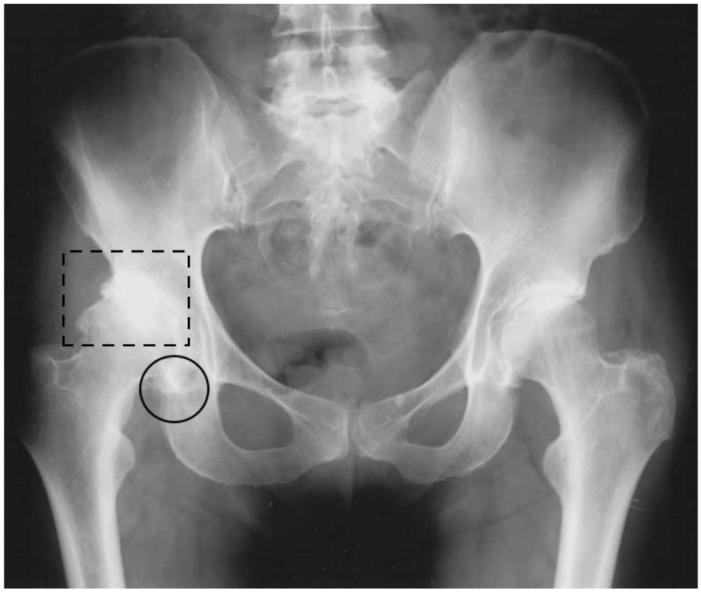


Figure 11: [27]

AP pelvic radiograph demonstrating the classical features of right hip osteoarthritis.

Note the joint space obliteration and marginal acetabular and femoral neck osteophytes in the dashed square, and the acetabular floor osteophyte in the black circle.

Osteophytes are bony excesses commonly seen on both the femoral and acetabular sides of hip affected by OA. The progressive development of osteophytes is thought to be a natural response by the body to increase the weight bearing surface area of the hip in order to reduce the load per unit area [32]. The position of these osteophytes should be noted as an attempt at removal should be made during the operation. Osteophytes may obscure the intra-operative field of view, distort anatomical landmarks, and mechanically block hip movement

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both pre- and post-operatively. Acetabular rim osteophytes may impinge on the native or prosthetic femoral neck, which may result in impingement type pain and dislocation following a THR. The presence of central acetabular osteophytes will impede the surgeon's ability to identify and restore the anatomical centre of rotation of the hip, and will need to be removed.

Bone cysts are also known as subchondral cysts, pseudocysts, or geodes. Degenerative subchondral acetabular cysts are a common finding in patients with primary osteoarthritis of the hip, and they mainly occur in the superior weight-bearing region of the acetabulum [33, 34]. In radiological terms, a bone cyst is a circumscribed area of translucency of the bone. The pathology of the cysts was described in detail by Landells in 1953 [35]. Landells hypothesised that cysts were formed by defects in the cancellous trabeculae, which yield under the pressure and thereby allow the intrusion and transmission of synovial fluid into enlarged marrow spaces. However, Rhaney & Lamb outline their view that bone destruction precedes the entrance of synovial fluid, and that the fluid-filled cystic cavities filled are formed in the course of the repair process as the dead bone is removed [36]. The results of a finite element analysis study in 2004 supported the theory that stress-induced bone resorption may cause the development of subchondral bone cysts in osteoarthrosis [34].

In primary THR, the location, size and containment of acetabular cysts and bone deficiencies are more important to note than femoral head cysts, which will be excised en-bloc following the femoral neck osteotomy. Femoral and acetabular bone loss can be described according to the Paprosky classification, which has been proven to be valid and reliable [37-41]. Isolated, contained acetabular bone deficiencies may be curetted intra-operatively and packed with autologous bone graft from, for example, the femoral head. Uncontained acetabular bone deficiencies may require more complex reconstruction, such as impaction bone grafting, trabecular metal augments, or gap cups or cages. If uncontained bony defects are suspected then a pre-operative CT scan must be obtained in order to define these accurately and prepare accordingly.

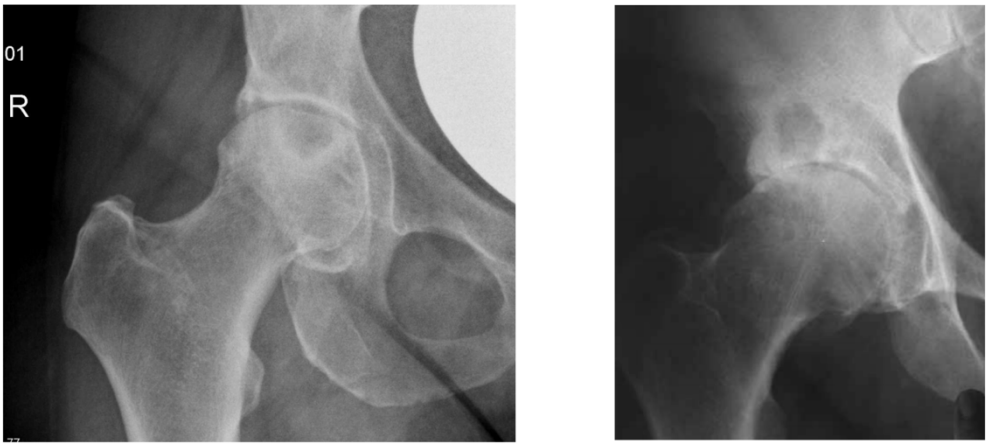


Figure 12:

Right hip radiographs demonstrating a femoral head cyst (left), and acetabular cyst (right)

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Step 5: Determine the implant sizes and ideal placement in order to recreate the patient's native hip anatomy

Acetabular cup

The rules for selection and positioning of the acetabular cup are as follows:

1) The lower edge of the cup should not be lower than the acetabular teardrop in the vertical plane.
2) The cement mantle (if using cemented), or outline of the acetabular cup (if using uncemented) should lie just outside of the line of the subchondral bone superiorly.
3) The cup should be contained within the supero-lateral margin of the acetabulum (unless there is a bone defect).
4) Cup inclination should be 40-50° in the coronal plane.
5) Cup anteversion should be 10-20° in the transverse (axial) plane.
6) Bony coverage of the cup should be 80%.
7) The cup should sit adjacent to, and not be medial to, the ilio-ischial (Köhlers) line in the horizontal (transverse) plane.

If using a cemented acetabular cup, then markings are placed around the cup to indicate the thickness of the cement mantle. Most cemented acetabular cups, will have multiple polymethylmethacrylate (PMMA) cement spacer 'dimples' located around the periphery of the cup, which prevent it from bottoming out on insertion. These can be seen in figure 18 and 19 below for the Stryker® Exeter Contemporary and X3 RimFit cups. The acetabular cup size refers to the outer diameter of the cement spacers and includes a 2-3mm cement mantle.



Figure 13: The Stryker® Exeter Contemporary cup demonstrating the PMMA spacer dimples

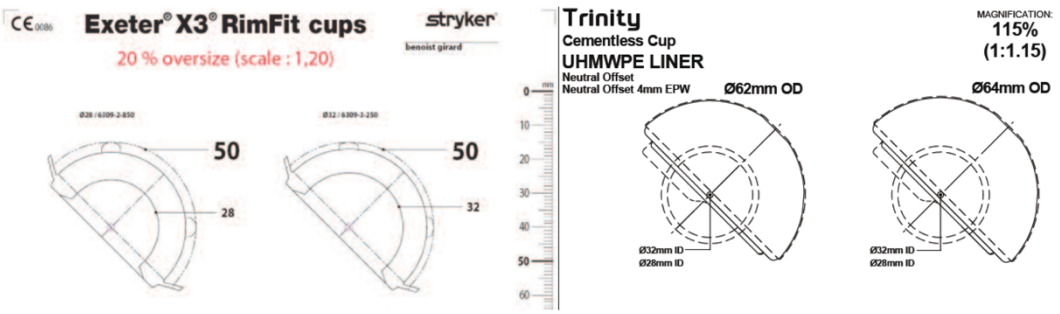


Figure 14: Examples of both cemented (left) and uncemented (right) acetabular cup templates

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If using an uncemented acetabular cup then the cup size selected should be either equal to or 1mm greater the final reamer size used, depending upon the manufacturer's specification. Any discrepancy in size of cup to reamer is accounted for by the hydroxyapatite (HA) coating on the acetabular cup. For example, the Trinity™ shell from Corin®, including coating, is 1mm larger than the nominal size (as labelled). To achieve a 1mm press-fit in hard bone the acetabulum should be reamed line to line with the nominal cup size. In order to achieve a 2mm press-fit, it is recommended that the surgeon reams 1mm less than the nominal size.

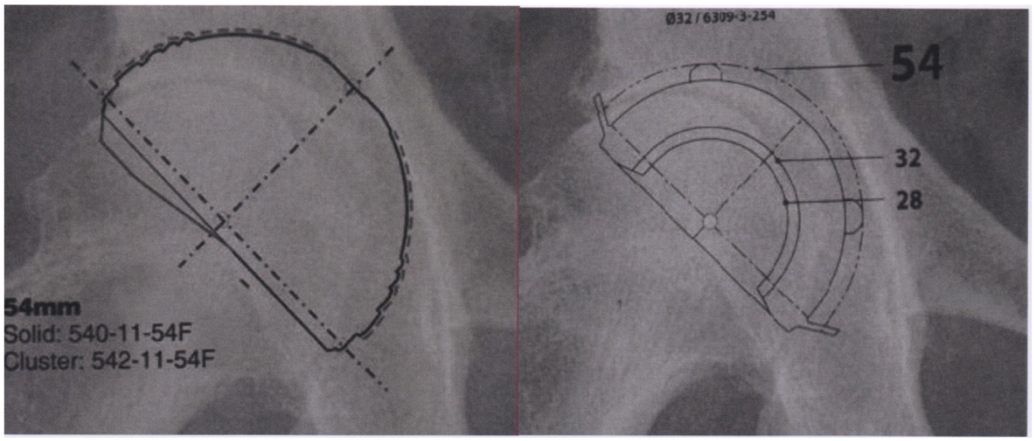


Figure 15: Examples of both cemented (right) and uncemented (left) acetabular cup templates

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Femoral stem

The rules for selection and positioning of the femoral stem are as follows:

1. The stem size selected should:
    a. Allow for an adequate complete cement mantle (2mm) around the entire prosthesis if using a cemented stem.
    b. Press fit against the inner femoral cortex if using an uncemented stem.
2. The femoral offset (FO) chosen must restore the COR of the femoral head.
3. The depth of the femoral stem must be planned in order to restore normal leg length.
4. The level of the femoral neck osteotomy must be planned. This is especially important in order to recreate leg length if using an uncemented or collared prosthesis.

Stem size: cemented

When using a cemented stem, such as the Corin® Taperfit™, or Stryker® Exeter V40™ the templates may have markings on either side of the stem to indicate the space which should be occupied by the cement mantle.

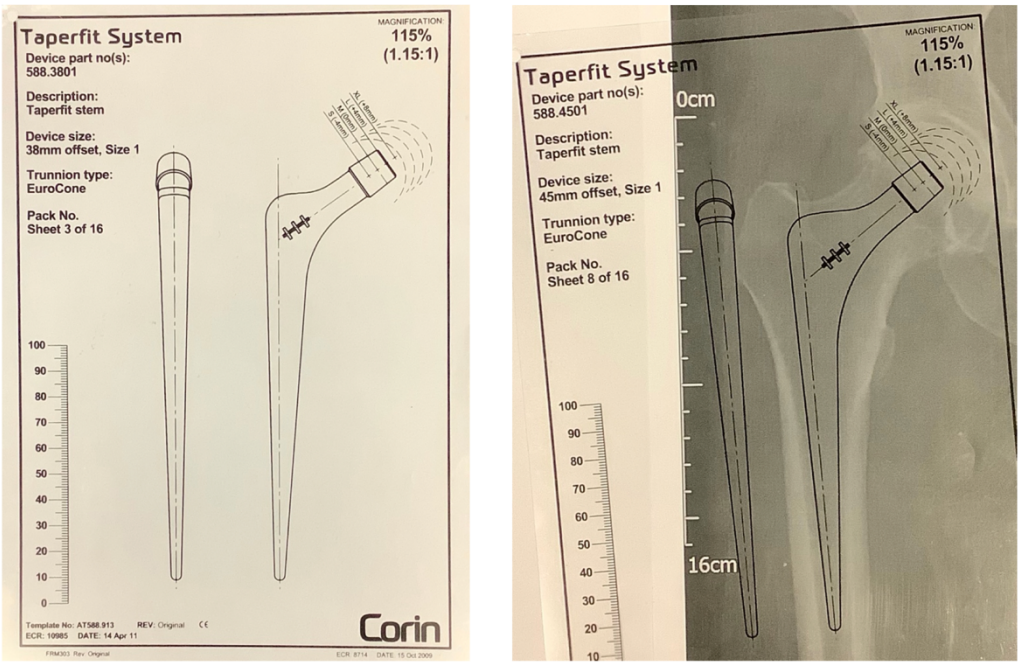


Figure 16: Pre-operative template of the Corin® Taperfit™ stem

At least one 'cement mantle' marking should lie within the inner femoral cortex at all points of the prosthesis in order to allow a sufficient cement mantle. If all cement mantle markings lie outside of the inner femoral cortex the stem is oversized. If there is excessive room outside of the cement mantle markings, then the stem is undersized.

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Stem size: uncemented

When using a cemented stem, such as the Corin® Trifit™, the size of the stem selected on templating must allow contact between both the medial and lateral endosteal cortices in order to achieve a 'press-fit'.

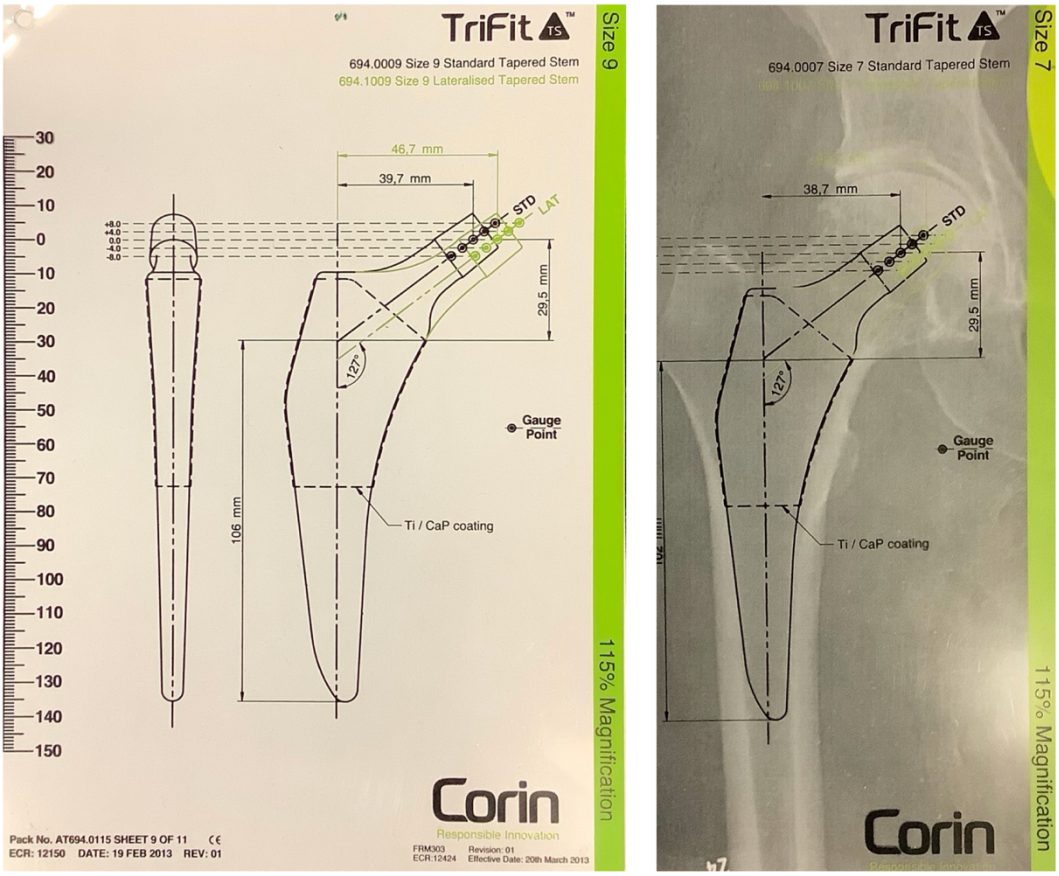


Figure 17: Pre-operative template of the Corin® Trifit™ stem

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Femoral offset and Centre of rotation for both cemented and uncemented stems

The COR of the femoral head can be made by overlaying the stem/head template on the proximal femur of the pelvic radiograph. This can be estimated even if there is bone loss on the superior aspect femoral head as there is usually enough outline of the head's sphericity remaining to estimate the COR. Alternatively, the contralateral proximal femur can be used to template if this is not diseased. If there is a significant distance between the femoral and acetabular COR in the transverse plane (see figure 18) then the offset of the femoral stem should be adjusted accordingly in order to recreate the femoral head COR (see figure 19).

Femoral stems come in a range of offsets (e.g. low, standard, high) which are either fixed (such as the Corin® Taperfit™ and Stryker® Exeter V40™), or increase gradually along with the size of the stem (Corin® Trifit™). Some stems such as the Corin® Trifit™ also offer extended neck lengths (standard and lateralised).

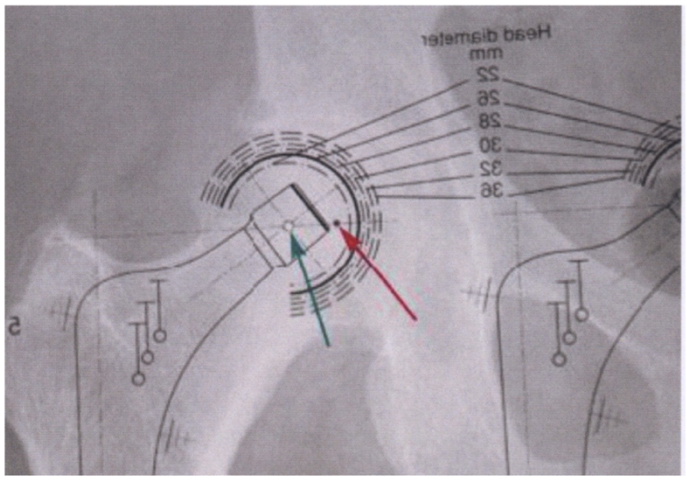


Figure 18: This stem has an undersized offset and does not place the COR of the stem (marked by the green arrow) in the anatomical COR of the femoral head (marked by the red arrow)

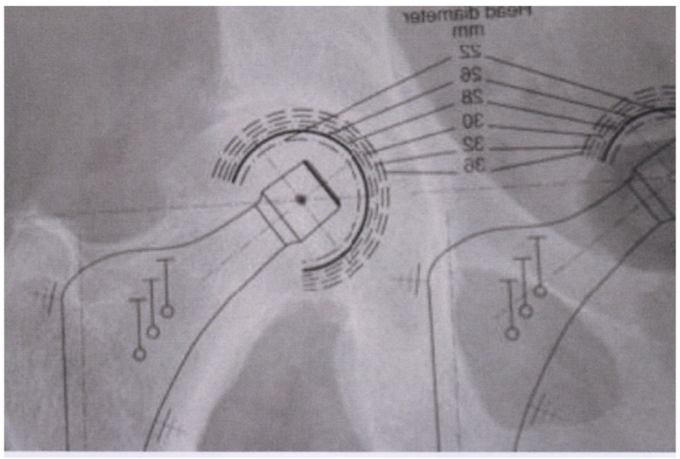


Figure 19: This stem has a satisfactory offset.

The COR of the prosthesis lies in the anatomical COR of the femoral head

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Depth of the stem insertion

After selecting the correct size and offset of the stem, the depth to which it should be inserted may be templated. The technique for this has been described by Wilson and the Exeter group [42, 43]. This is marked on the radiograph as the position of the shoulder of the stem in relation to a fixed anatomical landmark, such as the tip of the greater trochanter, after the template of the correct sized stem has been positioned optimally in order to recreate the FO and femoral COR. The distance in millimetres (mm) between the shoulder of the stem and the anatomical landmark chosen can then be measured using the ruler on the template and can be measured intra-operatively before the trial reduction.

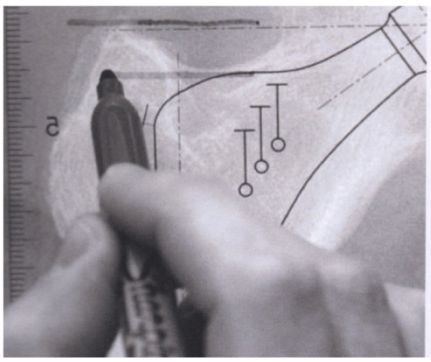


Figure 20: The ideal depth of the femoral stem can be marked and measured in comparison to the either the greater or lesser trochanters [42]

When using an uncemented stem, the level of the femoral neck osteotomy largely dictates the stem depth, especially if using a collared prosthesis. Intra-operatively the level of the femoral neck osteotomy may be judged using a mechanical guide and marked using diathermy (see figure 20).

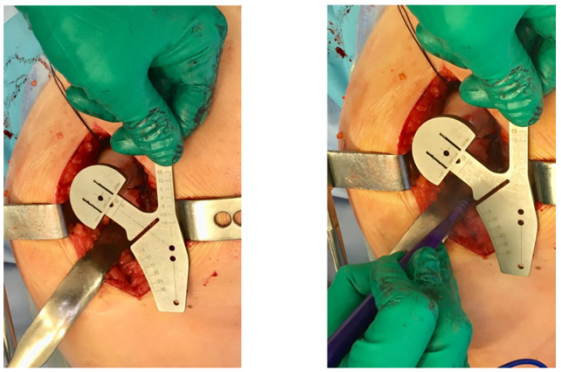


Figure 21: Assessment and marking of the level of femoral neck osteotomy when using an uncemented stem

The morphology of the proximal femoral canal should be noted in pre-operative planning and templating. The Dorr classification describes the structural bone quality of the proximal femur [44]. This classification uses the cortico-cancellous (CC) ratio, which is also known as the cortical thickness index (CI), in order to classify the type of proximal femoral bone quality and morphology. This is calculated by measuring the cortical width (CW) and endosteal width (EW) at a point 10cm distal to the lesser trochanter. Please see appendix for further details regarding the Dorr classification.

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Patient positioning & set-up

Patients can be positioned either supine or in the lateral decubitus position for THR. The majority of THR's in the UK are performed with the patient in the lateral decubitus position, which allows for either posterior or direct lateral surgical approaches to be used [46]. Careful patient positioning is critical in order to optimise acetabular component positioning and orientation [47].

Following induction of anaesthesia, the patient is carefully turned onto their side, with the hip to be operated on facing upwards towards the surgeon. The pelvis should lie vertically (perpendicular to the long axis of the table) in the middle of the operating table. With the patient manually stabilised in this position by surgical or theatre assistants, the primary surgeon may adjust the position of the pelvis before clamping both anterior and posterior side supports onto the side rails of the surgical table at the level of the lumbro-sacral junction posteriorly, and anterior superior iliac spines (ASIS) anteriorly if twin anterior posts are used (as recommended). If only a single anterior post is available then this should be positioned either over the uppermost ASIS or pubic symphysis. A padded posterior pelvic support is usually applied first over the lumbro-sacral junction and fixed in position. Following this the padded anterior post/s are applied with gentle pressure placed over the patient's ASIS. These posts should secure the patients pelvis perpendicular to the operating table, with the patients ASIS's orientated vertically with respect to each other in both the coronal and sagittal planes. The fastening knobs on both the clamps and posts should then be re-checked to ensure they are tight, which will reduce the chance of the patient's pelvis inadvertently moving during the operation. Any pelvic tilt at this stage may compromise the surgeon's perception of the pelvic position intra-operatively and lead to component mal-positioning [48].

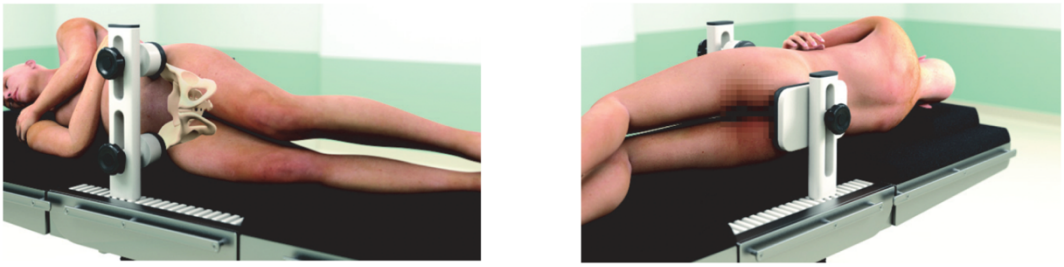


Figure 22: Patient positioning for primary THR (anterior and posterior views) [47]

Mechanical alignment guides (MAG's) used for both acetabular and femoral preparation and implantation are referenced off the patient's position. Therefore, any deviation in patient positioning, or movement of the patient intra-operatively will render these alignment guides inaccurate, and compromise intra-operative component positioning. A wide variability in patient positioning, set-up, and movement intra-operatively, have been shown to contribute to inconsistent acetabular cup positioning during THR [49].

The ipsilateral arm should be stabilized with a padded arm board. A padded axillary roll should be placed under the contralateral chest wall to avoid brachial plexopathy [50]. Following this, a pillow may be placed between the patient legs in order to protect pressure areas. The pillow should not obscure the knees as these will need to be palpable under the drapes for leg length estimation intra-operatively.

The primary surgeon should then carefully assess the patients leg length in this position. As the leg to be operated on will lie in an adducted position relative to the pelvis this will create the impression of leg shortening.

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Skin preparation, draping, and antibiotic administration

Good surgical practice in skin preparation, sterile draping technique, and the administration of appropriate antibiotics pre-operatively are all key factors in reducing the risk of contamination, and resultant superficial and/or deep surgical site infections. Elective THR is classified as clean surgery, and in 2011 the UK Health Protection Agency (HPA) reported an 0.8% incidence of SSI in elective THR. Although a range of skin antisepsis formulations are commercially available, we recommend the use of 2% chlorhexidine gluconate in 70% isopropyl alcohol.

Following patient positioning and prior to skin preparation, any significant hair overlying the surgical site should be removed using electrical clippers in the anaesthetic room.

Following transfer and positioning of the surgical table in the operating room, a theatre assistant should hold the operative leg by the calf or under the knee in an abducted and slightly externally rotated position for preparation of the foot and ankle using the chosen antiseptic solution on a sponge or gauze held with forceps. Absorbent pads should be placed under the leg temporarily whilst draping to prevent the collection and pooling of antiseptic solution. Following preparation of the foot and ankle, this can be held by the scrub staff or surgical assistant using either a swab soaked in antiseptic solution, or within an unrolled stockinette whilst the remainder of the operative leg is prepped. Sterile 'table cover' sheets are then placed on the table underneath the operative leg, and another above the level of the iliac crests superiorly before the sterile surgical drapes are applied. Disposable non-woven drapes are superior to reusable woven cotton/linen drapes in resisting bacterial penetration [51]. A sterile sticky plastic U drape is first applied underneath the leg, with the leaflets of the drape pointing towards the patient's head. The sticky leaflets of the U drape are applied inferiorly, anteriorly and posteriorly to effectively seal off the perineum, and the remainder of the drape unfolded distally. Attention must be paid to position the posterior leaflet of this drape to allow leave sufficient room across the buttock to extend the incision posteriorly and superiorly. A second larger sterile extremity U drape is then placed underneath the leg in a similar fashion, but with the sticky edges lying on the skin just within the margins of first U drape. A large utility drape is then applied superiorly across the patient's side, above the iliac crests. The leg stockinette may then be rolled up to above the knee and secured using a sterile crepe bandage. A further hip drape (with a hole cut out in it) may then be placed. If used, the hip drape will often incorporate a side leg bag used for leg positioning in the direct lateral (Hardinge) approach. Skin from the mid-thigh distally to the iliac crest proximally should be left exposed in case extension of the incision is required during the operation. The position of the drapes may then be secured using an Ioban™ or similar occlusive sticky dressing. The operative leg should remain mobile and free to manoeuvre, which will facilitate the visualisation of key structures throughout the operation. Following draping, the surgeons, assistants, and scrub nurses' top gloves should be changed and the skin may then be marked by the surgeon prior to performing the surgical approach.

The administration of systemic antibiotics according to local Hospital Trust antimicrobial guidelines should routinely take place prior to skin incision for THR [52]. A systematic review and meta-analysis investigating the use of antibiotics in patients undergoing THR reported that preoperative systemic antibiotic prophylaxis in primary THR may be effective at reducing infection rates [53]. Furthermore, if using cemented prostheses, then the use of antibiotic loaded bone cement has also shown to reduce the incidence of PJI [54].

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Anatomy of the Hip, Skin Incision, & Surgical Approach

The surgical approach for primary THR should allow excellent exposure of the proximal femur and circumferentially around the acetabulum. Although a number of surgical approaches for primary THR have been described, the most commonly performed are the posterior (Moore or Southern), direct lateral (Hardinge), or direct anterior (Smith-Peterson) surgical approaches. Each surgical approach has its own advantages and risks. A worldwide consensus on surgical approaches and prosthesis fixation for total hip arthroplasty reported that 45% of Surgeons favoured the posterior approach, 42% the direct lateral approach, 10% the direct anterior approach, and 3% other approaches [55]. Within the United Kingdom, the most commonly utilised surgical approach for a primary THR is the posterior approach, which we recommend. For the purposes of this workbook we will provide an overview of the steps involved in performing both the posterior and direct lateral approaches to the hip joint for elective primary THR. We have used illustrations and text from the online AO Foundation Educational pages to help outline the key stages of each approach (https://www2.aofoundation.org).

Anatomy of the hip and proximal femur

The acetabulum forms the convergence of three separate bones, namely the ilium (superiorly), ischium (posteriorly), and pubis (anteriorly). The acetabular fossa, also known as the cotyloid fossa, forms the central non-articular aspect of the acetabulum below the acetabular roof [56].

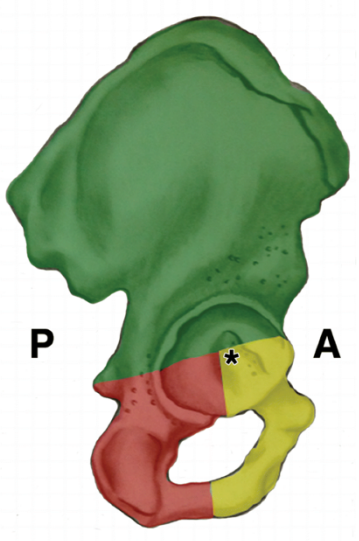


Figure 23: Lateral view of the right hemi-pelvis demonstrating the 3 bones which from the acetabulum: the ilium (green), ischium (red), pubis (yellow), and acetabular/cotyloid fossa (*)

The muscles of the hip joint and thigh are enclosed beneath the fascia lata. The superficial gluteal muscles (maximus, medius, and minimus) along with adipose tissue make up the bulk of the buttock, and their origin, insertion, neurovascular supply and action is outlined in a table in the appendix. The posterior third of gluteus medius is covered by gluteus maximus, and the anterior two thirds is covered by the gluteal aponeurosis. The gluteal bursae (trochanteric, gluteofemoral, and ischial) are membranous fluid filled sacs which provide protection for the muscles and tendons from attritional damage as they pass over or around bony structures.

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The anterior thigh muscles comprise of the tensor fascia lata, quadriceps (rectus femoris, and vastus lateralis/medialis/intermedius), sartorius, and iliopsoas. The posterior thigh muscles comprise of the hamstrings (biceps femoris, semi-membranosus, and semi-tendinosis). Details of the anatomy of the anterior and posterior thigh muscles will not be covered in further detail in this workbook.

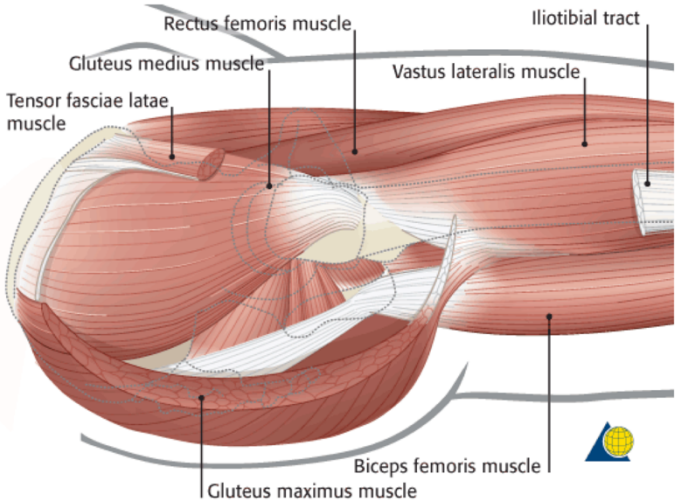


Figure 24: Pictorial view of the superficial muscles surrounding the hip

Deep to the gluteal muscles lie the short external rotators (SER's) on the posterior aspect of the proximal femur. They all act to adduct and externally rotate the thigh, and stabilise the femoral head in the acetabulum. The tendinous portions of these muscles should be identified as they insert onto the medial border of the proximal femur, and at a minimum the piriformis should be tagged with a suture prior to division during the posterior approach to the hip joint.

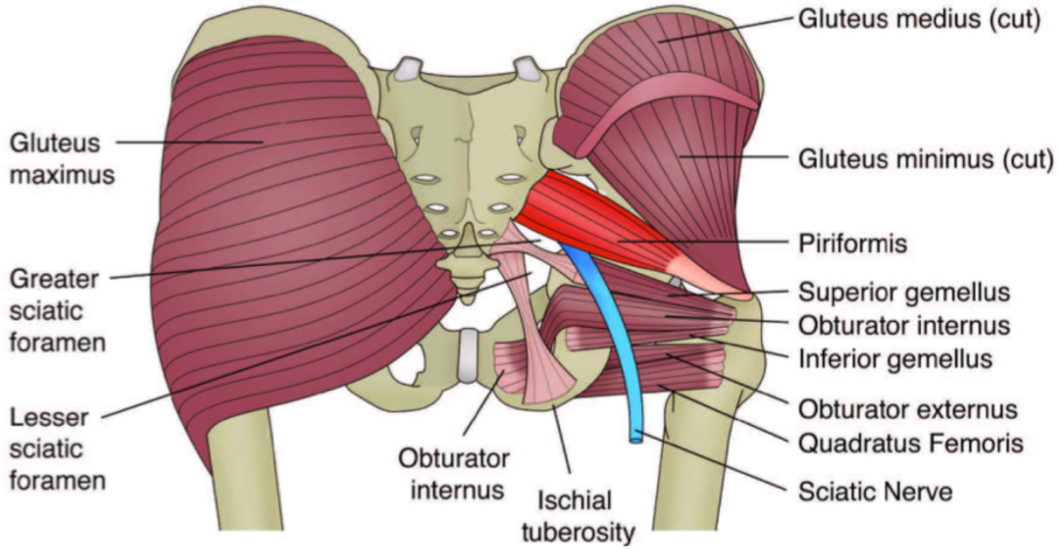


Figure 25: Pictorial view of the short external rotators of the hip

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Hip capsule

The hip capsule is a strong and dense fibrous structure which surrounds and encapsulates the hip joint and contains synovial fluid for joint lubrication. The hip joint capsule is tight in extension and more relaxed in flexion. The capsule consists of two sets of fibres:

1) The circular fibres (zona orbicularis). These form a sling around the neck of the femur.
2) The longitudinal fibres, which are thickest anteriorly and superiorly along the capsule.

Thickening of the longitudinal fibres forms three ligaments, which help stabilise the hip. These are the:

1) Ilio-femoral ligament (of Bigelow): A Y-shaped structure located anteriorly, which is the strongest ligament in the body. This prevents excessive hip extension.
2) Pubo-femoral ligament. This prevents excessive hip abduction and extension.
3) Ischio-femoral ligament. This prevents excessive hip extension.

The capsule is attached anteriorly to the femur at the intertrochanteric line, and posteriorly on the medial half of the femoral neck. The lateral half of the femoral neck is extracapsular. On the pelvis the capsule is attached 5-6mm above the superior margin of the acetabulum, and inferiorly it is connected to the transverse acetabular ligament.

Sciatic nerve

The sciatic nerve (SN) is the longest and thickness single nerve in the human body [57]. It is derived from both the anterior and posterior divisions of the lumbosacral plexus (L4-S3). The SN normally exits the pelvis through the greater sciatic notch below and ventral to the piriformis muscle and travels across the dorsal aspect of the remaining SER's down the posterior compartment of the thigh deep to biceps femoris and superficial to adductor magnus to reach the popliteal fossa, where it divides into its terminal branches – the tibial nerve (TN), and common peroneal nerve (CPN). Variations in the anatomy of the SN have been well described, and are these are categorised based upon the relationship of the SN to the pirformis muscle [57]. The two most common variants, which constituted 95% in a pooled meta-analysis of studies, are:

1) The SN exits the gluteal region as a common trunk (type A, 85.2%) below/ventral to the piriformis muscle.
2) The SN bifurcates within the pelvis into the CPN and TN divisions, with the CPN piercing the piriformis tendon, and the TN coursing below and ventrally to the piriformis muscle (type B, 9.8%).

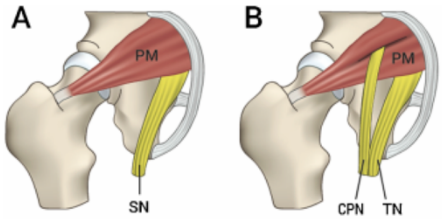


Figure 26: Pictorial view of the two most common anatomical variants of the sciatic nerve

The most common iatrogenic nerve injury during THR is damage to the peroneal division of the sciatic nerve, followed by the superior gluteal, obturator, and femoral nerves [58].

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Posterior approach to the hip joint

The posterior approach to the hip joint was popularised by Moore in the 1950's [59, 60]. The advantages of the posterior approach are that it is extensile to both proximally and distally, and also does not violate the hip abductors [61]. There is no inter-nervous plane with the posterior approach. The intermuscular interval involves sharp incision of the fascia lata and blunt dissection of the gluteus maximus fibres. The deep dissection involves meticulous dissection of the short external rotators and capsule [62]. Damage to the inferior gluteal artery is the main vascular risk, and damage to the sciatic nerve is the main neurological risk of the posterior approach [58]. A systematic review reported that the risk of post-operative dislocation following primary THR using a posterior approach with soft tissue repair is similar to the that seen with the direct lateral and antero-lateral surgical approaches [63].

Skin marking & incision

We recommend marking the skin with a sterile pen following prepping and draping prior the skin incision. With the patient secured in a lateral decubitus position and the hip flexed to 90º, a 12-15cm longitudinal line is drawn centred over the central to posterior third of the greater trochanter, which is palpable subcutaneously in most patients. The axis of the line drawn is along the middle of the femoral shaft distally, which can be continued proximally in the same line when the hip is flexed to 90º. When the leg is extended, the proximal half of the skin marking will be gently curved posteriorly relative to the femoral shaft axis. If marking the patient with the leg extended we recommend curving the proximal aspect of the skin marking approximately 30º posteriorly from the tip of the greater trochanter for patients with a normal NSA (126-139º). An anatomical landmark is to aim towards the posterior superior iliac spine (PSIS).

In patients with coxa valga (NSA >140º) we recommend a less posteriorly curved skin marking proximal to the greater trochanter, and in patients with coxa vara (NSA <125º) we recommend a more posteriorly curved skin marking proximal to the greater trochanter. This will provide a better exposure of the proximal femur following dislocation in order to perform the neck osteotomy, femoral preparation, and implantation.

Superficial Dissection

Following sharp dissection through the skin and subcutaneous fat the fascia lata is most easily identified at the level of the greater trochanter. Sharp dissection using a scalpel through the fascia should be started at this point and continued distally approximately 6cm in line with the skin incision along the line of the femoral shaft to expose the vastus lateralis muscle. Proximally the fascia and gluteus maximus should be split using a combination of sharp (scalpel) and blunt (scissors) dissection as required in line with its fibres (see figure 27).

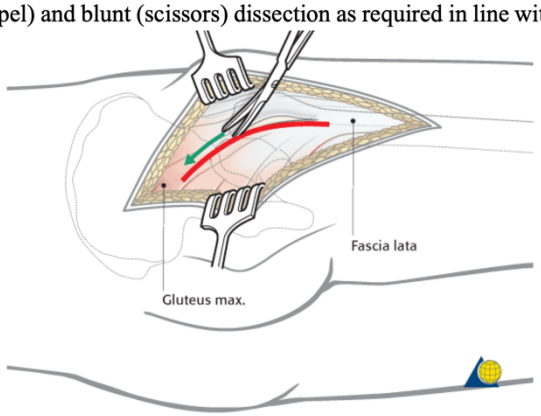


Figure 27: Posterior approach superficial dissection

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Deep Dissection

A Charnley retractor may now be placed carefully under the fascia and gluteus maximus muscle flap, taking care to palpate and avoid incarceration of the sciatic nerve under the teeth of the posterior retractor. If in doubt regarding the location of the sciatic nerve, the hip may be extended and the knee flexed, which will de-tension the nerve, and allow it to fall away from the surgical field. Further exposure of the sciatic nerve is not required or recommended in a primary THR, but it's identification, location, and fact that attempts have been made to protect it throughout the procedure should be made in the operative note. At this stage the patient's foot is placed onto a padded Mayo surgical table, which will internally rotate the leg and tension the SER's. The SER's are located inferior to the posterior fibres of gluteus medius, and are normally covered by a thin film of fat and leash of blood vessels. This fat may be gently and minimally swept away from the surface of the SER's using a swab, and any visible vessels cauterised using diathermy, which will improve visualisation (see figure 28).

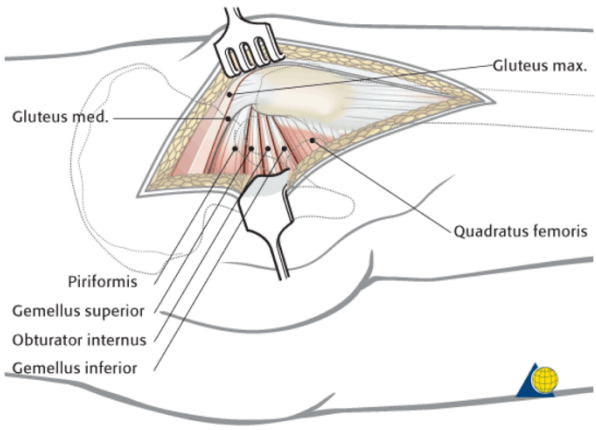


Figure 28: Posterior approach deep dissection

View of the SER's once the layer of fat has been swept away from their surface.

The first medial circumflex artery and vein cross the femur from posteriorly 5 cm distal to the trochanter in proximity to quadratus femoris. Damage to these vessels may cause significant bleeding and if encountered it should be ligated or cauterised prior to division of the SER's.

Either a blunt Hohmann retractor is placed underneath the gluteus medius muscle and over the superior aspect of the femoral neck, or a Langenbeck retractor placed underneath the gluteus medius muscle and elevated in order to visualise the superior aspect of the piriformis tendon, which may be hidden underneath the posterior fibres of gluteus medius. Following identification, the piriformis tendon is tagged using a heavy suture. This will facilitate later repair, and is also useful as an intra-operative marker of soft tissue tension in the assessment of leg length and femoral offset. Any remaining SER tendons which have sufficient quality and thickness (such as the conjoined tendons of obturator internus and inferior gemellus) may also be tagged in a similar fashion, however only the piriformis tendon is essential to tag and subsequently repair.

The SER's are then be released as close to their femoral insertion as possible along the postero-medial surface of the greater trochanter using diathermy. This is from the piriformis superiorly down to the mid-substance of the quadratus femoris distally. Following division and reflection of the SER's the posterior hip capsule will be visible. Reflection of the SER's also serves to protect the sciatic nerve from iatrogenic injury intraoperatively.

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The hip capsulotomy may be performed at the same time as dividing the SER's, however we would recommend that these be performed separately. This will allow clear identification of both structures for individual repair. A T- or H-shaped capsulotomy using either diathermy or a scalpel is recommended. The corners of the 'leaflets' of the capsule tagged with a heavy suture in order to facilitate later repair.

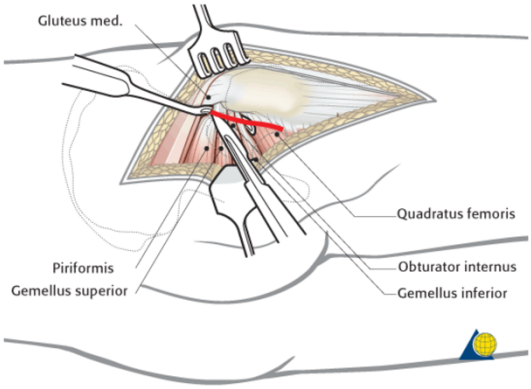


Figure 29: Posterior approach division of the SER's

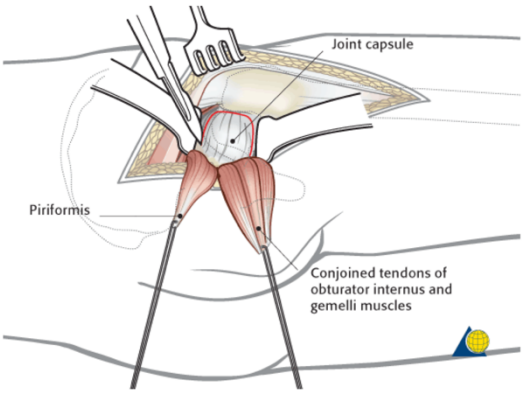


Figure 30: Reflection of the SER's and exposure of the posterior hip capsule

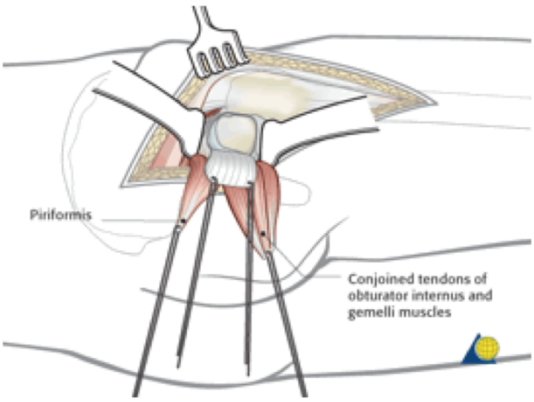


Figure 31: A U-shaped capsulotomy has been performed in this case.

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Hip dislocation

The hip joint may now be surgically dislocated by gently internally rotating, adducting and flexing the leg. If the hip cannot be easily dislocated then further soft tissue releases or resection of marginal osteophytes will be required, as excessive force during this stage of the operation may risk fracturing the femur.

A secure repair of the posterior hip capsule and piriformis tendon decreases the risk of post-operative dislocation following a posterior approach [63, 64]. This may be performed using the tagged structures, with the suture ends being passed through trans-osseous drill holes in the greater trochanter and tied off.

Direct lateral approach to the hip joint

The direct lateral, or trans-gluteal approach to the hip was popularised by Hardinge in 1982 [65]. This approach involves releasing the anterior third of gluteus medius and minimus and the proximal 5cm of vastus lateralis, while preserving the posterior femoral attachment of the major part of gluteus medius. There is no inter-nervous plane with the direct lateral approach. The approach involves splitting of the gluteus medius muscle distal to its innervation from the superior gluteal nerve, and splitting of the vastus lateralis muscle lateral to its innervation from the femoral nerve. Damage to the femoral vessels and superior gluteal artery are the main vascular risks, and damage to the superior gluteal nerve is the main neurological risk of the posterior approach [58]. A major potential disadvantage of this approach is the likelihood of some early postoperative abductor weakness that can slow rehabilitation, alongside the possibility of persistent abductor weakness and limping if the abductor layer repair fails [66].

Skin marking & incision

We recommend marking the skin with a sterile pen following prepping and draping prior the skin incision. With the patient secured in a lateral decubitus position a 12-15cm longitudinal line is drawn centred over the middle third of the greater trochanter, which is palpable subcutaneously in most patients. The axis of the line drawn is along the middle of the femoral shaft distally, which can be continued proximally in the same line, or curved slightly posteriorly.

Superficial Dissection

Incise the fascia over the palpable lateral border of the greater trochanter and extend proximally and distally in line with the skin incision. This is in the interval between the tensor fascia lata (TFL) and gluteus maximus muscle fibres. Keeping posterior to the tensor fascia lata prevents iatrogenic damage to this muscle. This will reveal the underlying gluteus medius and vastus lateralis muscles. Remove any trochanteric bursal tissue in order to improve visualisation of these muscles.

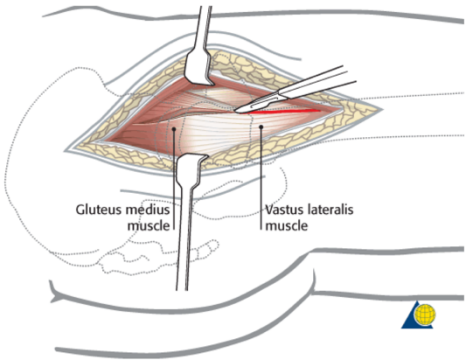


Figure 32: Direct lateral approach superficial dissection

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A Charnley retractor may now be placed carefully under the fascia and gluteus maximus muscles, taking care not to incarcerate the sciatic nerve. Any remnants of trochanteric bursal tissue may be removed to expose the underlying gluteus medius and vastus lateralis muscles.

Deep Dissection

Proximally a pair of Mayo blunt ended surgical scissors may be passed in the interval between the anterior third and posterior two-thirds of the gluteus medius muscle down to the femoral neck and opened to create a pocket from which to commence dissection medially in the muscle towards the femoral head and acetabulum. Split and reflect the proximal fibres of vastus lateralis and the anterior third of the gluteus medius muscle and tendon directly off the proximal femur using the diathermy to minimise blood loss. A full thickness flap of muscle and tendon down to bone should be taken in continuity along the course of the dissection, and care taken not to tangentially divide or delaminate the muscle. At the level of the greater trochanter the gluteus medius tendon should be split lateral to the musculotendinous junction, in order to provide a sufficient cuff of tissue for repair. This can be performed in an omega shape around the anterior border of the greater trochanter, or straight in line with the fascial incision over the greater trochanter. The tendon of gluteus minimus may also be identified underneath gluteus medius along the anterior border of the greater trochanter. If so, this should be tagged prior to division to facilitate later repair. Distally, the anterior fibres of vastus lateralis are elevated off the anterior femur to expose the intertrochanteric region. This should be no further than the level of the lesser trochanter in a primary THR. Gentle external rotation and adduction of the leg by the surgeon's assistant may help in visualisation during this dissection.

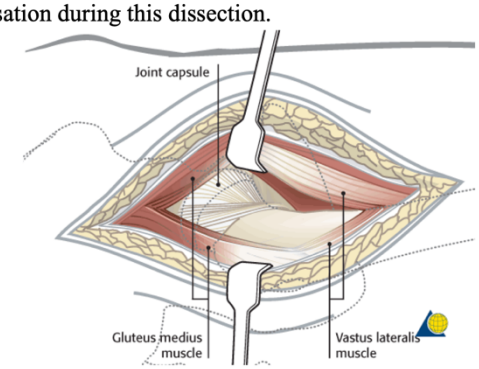


Figure 33: Direct lateral approach deep dissection

Full thickness flap of the anterior third of gluteus medius and vastus lateralis muscles

Take care not to extend the split of the gluteus medius tendon beyond 5cm proximal to the tip of the greater trochanter as this will risk damage to the superior gluteal nerve, artery, and vein [67].

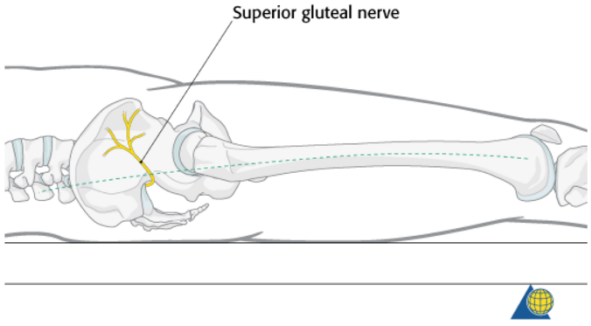


Figure 34: Path of the superior gluteal nerve (and vessels)

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Following dissection of gluteus medius and vastus lateralis, the anterior muscle flap may be carefully placed under the anterior teeth of the Charnley retractor or an additional self-retaining retractor placed in between to keep it from obscuring the view of the hip capsule. Excessive pressure should be avoided as it may induce tissue necrosis, post-operative pain and hetero-topic ossification. The anterior attachment of the hip capsule will then be visible. An anterior longitudinal T-shaped capsulotomy is performed, with antero-superior extension along the mid-axis of the femoral neck up to the anterior lip of the acetabulum, and antero-inferior extension to the intertrochanteric region. The superior and inferior 'leaflets' of the capsule may be tagged with a suture in order to facilitate later repair.

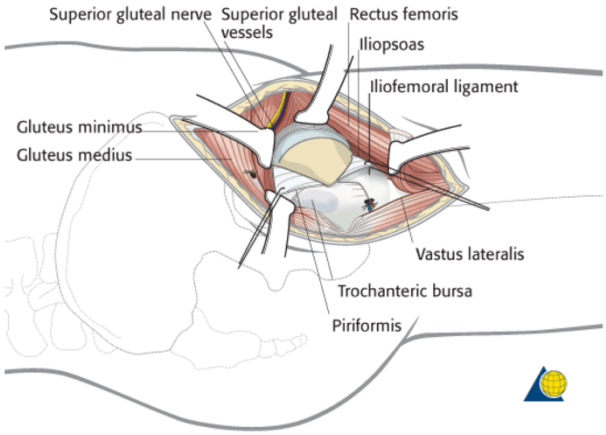


Figure 35: T shaped capsulotomy prior to surgical dislocation of the hip

Hip dislocation

The hip joint may now be surgically dislocated by gently externally rotating and flexing the hip and knee into a sterile bag on the contralateral side of the table in a 'figure of four' position. If the hip cannot be easily dislocated then further soft tissue releases or resection of marginal osteophytes are required. A bone hook may also be placed around the femoral neck to assist dislocation using an anterolaterally directed force. Excessive force during this stage of the operation may risk fracturing the femur.

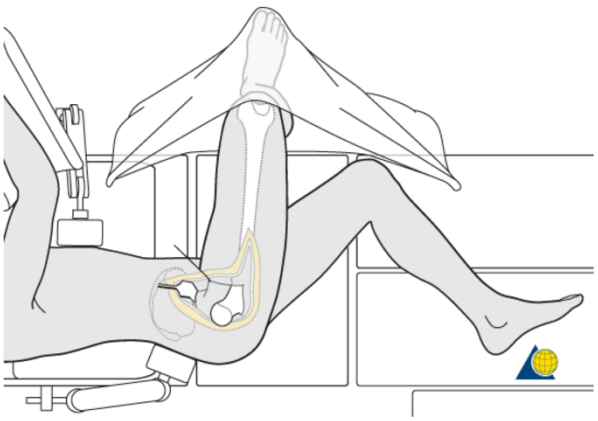


Figure 36: Figure of 4 position for surgical hip dislocation during the direct lateral approach

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Acetabular exposure, preparation & implantation

Acetabular Exposure

A circumferential view of the acetabulum must be established prior to reaming and component implantation.

Positioning of retractors for acetabular exposure

Careful positioning of Hohmann and self-retaining retractors in the following positions around the acetabulum is required in order to visualise key structures prior to reconstruction:

Anterior retractor:

- Placed carefully over the anterior-superior acetabular ridge deep to the capsule and directly onto bone.
- Do not place retractors anteriorly onto or beyond the iliopsoas muscle or tendon as this risks iatrogenic damage to the femoral nerve and vessels.
- This retractor also functions to move the proximal femur anteriorly out of the way of the acetabulum when performing a posterior approach.

Inferior retractor:

- Placed carefully below the transverse acetabular ligament (TAL) at the inferior margin of the acetabulum.
- This retractor risks injuring the obturator nerve and vessels.

Superior self-retaining retractor (Norfolk & Norwich)

- The teeth of this self-retaining retractor are placed superiorly under the capsular flap and gluteus medius muscle, and posteriorly under the posterior capsular flap and SER's.
- This retractor exposes the superior and posterior aspects of the acetabulum.

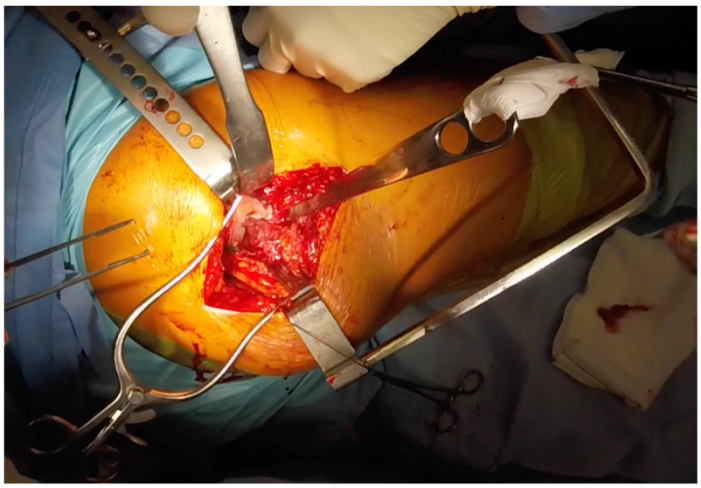


Figure 37: Position of the retractors for optimal acetabular exposure

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Additional soft-tissue releases

The anterior hip capsule may be tight in OA, and careful release over the anterior lip of the acetabulum may be performed using either a Cobb elevator, a long-handled scalpel or diathermy, which will facilitate anterior retraction. The reflected head of rectus femoris may also be tight over the anterior capsule. This may be released using a scalpel or diathermy to facilitate anterior retraction.

Labral resection/osteophytectomy

A self-retaining retractor (such as a Norfolk & Norwich) may be placed under the 'leaflets' of the capsule in order to expose the entirety of the acetabular labrum. This should be sharply excised circumferentially to expose the bony acetabulum using a long-handled scalpel. The edge of the blade should remain pointed inwards towards the centre of the acetabulum throughout.

Large peripheral acetabular osteophytes may be removed using osteotomes. However, if in doubt these can be identified and excised following reaming and uncemented component trialling or implantation as they will become increasingly obvious as structures overhanging the rim of the cup. These peripheral acetabular osteophytes are a common cause of impingement and levering, which may be a factor in post-operative dislocation.

Reaming

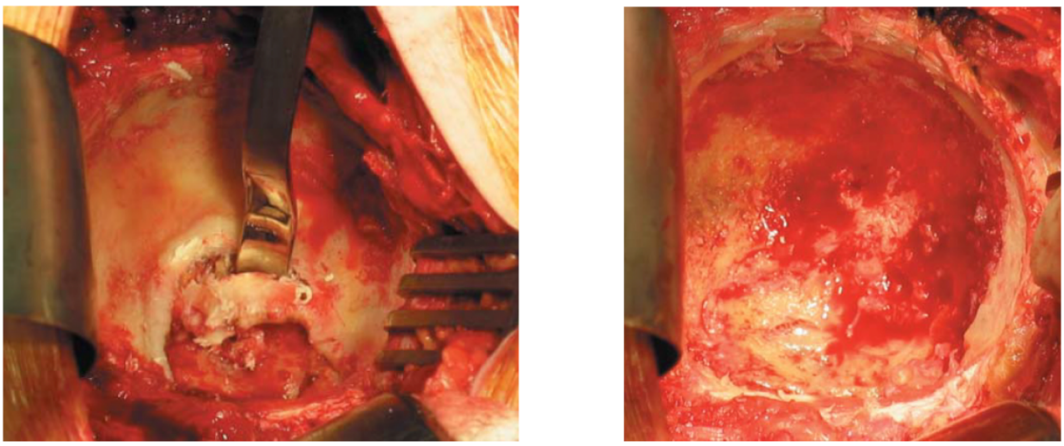
Any remaining stump of the ligamentum teres, pulvinar, and acetabular cartilage requires excision using a spiked ring curette or forceps and diathermy prior to reaming. If the pulvinar or TAL is calcified or medial acetabular osteophytes exist then these may block the view of the cotyloid fossa and require excision using either a bone curette or Capener gouge (see figure 38A).

Once the cotyloid fossa is visible the smallest 'starter' reamer (usually 40 or 42mm) can be used. This should initially be directed medially at the level of the cotyloid fossa in order to deepen and identify the medial wall (true floor) of the acetabulum. This point represent the appropriate medial margin or floor of the cup placement, and no further reaming should be performed medially to this point.

After deepening/medialising of the acetabulum concentric expansile reaming should be performed in order to create a hemi-spherical acetabulum with visible bleeding cancellous bone in the correct orientation to receive the cup (40-50° inclination and 10-20° anteversion).

The surgeon's lower hand, which is positioned on the reamer handle should steady the level of the inferior margin of the reamers position at the level of the TAL. This is usually provided by gentle anterior inferior pressure from the hand placed on the handle of the reamer. This will prevent superior or posterior migration of the reamer, which will inadvertently raise the centre of cup placement and risk reaming out the posterior wall, which is particularly at risk when utilising a posterior approach. The direction of the reamer should be parallel with the TAL (usually 10-20º anteverted) with an inclination of 40º. Continue reaming up in increments of 2mm until the sclerotic subchondral bone is removed and bleeding cancellous bone is visible concentrically within the acetabulum (see figure 38B).

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A **B**

Figure 38:

Figure A: Removal of acetabular floor osteophyte using gouge to expose cotyloid fossa

Figure B: Circumferential bleeding cancellous bone is visible following acetabular reaming

It is particularly important to be careful not to ream out either the anterior or posterior walls, which will compromise the final position and stability of the acetabular cup. The posterior wall is usually at greater risk, as the reamer is usually directed posteriorly in order to achieve the desired 20º anteversion. If in doubt stop and assess the thickness of the walls by palpating between your index finger and thumb. Application of gentle anterior pressure from the surgeon's hand on the handle of the reamer is helpful to prevent posterior drift whilst reaming.

Any subchondral cysts that are exposed during reaming may be curetted and packed with autologous bone graft harvested from the excised femoral head.

Uncemented cup trialling, sizing & positioning

Uncemented acetabular component trials may be placed using the introducer and mallet in order to ensure that a press fit is achieved circumferentially. Asymmetric acetabular reaming and soft tissue impingement are two common cause for the cup not fitting properly. Beverland *et al* have suggested that the definitive acetabular component should not be more than 4mm larger than the native femoral head [47]. Post-operative pain has been associated with oversized acetabular cups, with a study by Odri *et al* suggesting a cut-off value of >6mm than the native femoral head [68].

In the Corin® Trinity™ system the acetabulum should be reamed 'line to line' to fit the implant (i.e. a 50mm final reamer should be used with a 50mm Trinity™ cup. The Trinity cups have a 1.0mm peripheral coating (e.g. 52mm shell = 53.0mm periphery at the rim of the shell), in order to allow a press-fit. In the Stryker® Trident™ system, 'line to line' reaming is also recommended, however the Trident PSL shells have a 1.8mm oversize periphery (e.g. 52mm shell = 53.8mm periphery at the rim of the shell), in order to allow a press-fit. This may make impaction and seating difficult particularly in dense hard bone, and 1mm additional reaming may be required in these circumstances, if achieving a press-fit may risk iatrogenic acetabular fracture.

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The optimal position of the acetabular cup should already be known from pre-op templating. A reminder of the rules for positioning are as follows:

1. The lower edge of the cup should be at the level of the transverse acetabular ligament (TAL).
2. The cement mantle (if using cemented), or outline of the acetabular cup (if using uncemented) should lie just outside of the line of the subchondral bone superiorly.
3. The cup should be contained within the supero-lateral margin of the acetabulum (unless there is a bone defect).
4. Cup inclination should be 40-50° in the coronal plane.
5. Cup anteversion should be 10-20° in the transverse (axial) plane.
6. Bony coverage of the cup should be 80%.
7. The cup should sit adjacent to, and not be medial to, the ilio-ischial (Köhlers) line in the horizontal (transverse) plane.

Uncemented cup implantation

It is good surgical practise to change gloves before handling any prosthesis prior to insertion.

Once the correct size cup has been selected and mounted on the introducer, we would recommend using the alignment guide, which is supplied on both the Corin® Trinity™ and Stryker® Trident™ equipment trays. This may be used to optimise the final positioning of the acetabular component (40-50° inclination and 10-20° anteversion), but is dependent upon a knowledge of the patients position on the table, as outlined in the earlier section on positioning. Avoid touching the backside of the cup against the skin or other surfaces during insertion.

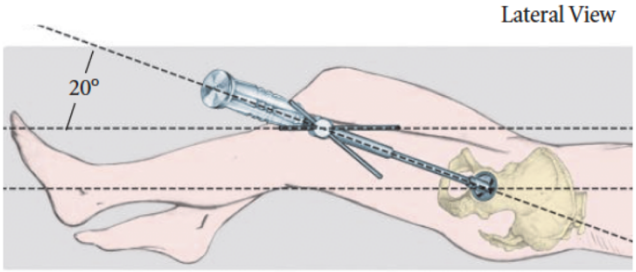


Figure 39: Lateral view of the acetabular cup alignment guide to optimise component version

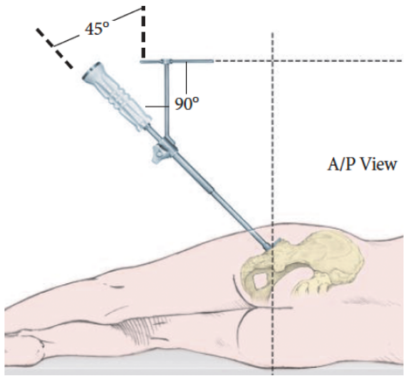


Figure 40: AP view of the acetabular cup alignment guide to optimise component inclination

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The cup should be rotated clockwise into the prepared acetabulum in order to clear any peripheral soft tissue, paying particular attention to the final position of the screw holes (if present) and overall inclination and version of the cup. The optimal position of acetabular screws is covered in the next section. Once the optimal position has been achieved, ideally the surgeon maintains this position and the assistant impacts the cup using a mallet. The bone-implant interface fixation should be strong enough to be able to maintain the position of the introducer without the support of the surgeon's hand. If not remove the cup and again check for any peripheral soft tissue interposition.

Following successful placement of the cup, the introducer may then be unscrewed and the depth (medialisation or 'bottoming-out') of the cup checked by placing the tips of a pair of forceps through the introducer hole to feel the cancellous bone on the reamed acetabular surface. If the cup is not fully medialised/bottomed out, then the introducer may be re-applied and further impaction delivered using the mallet.

At this stage acetabular screws holes may be placed if required for additional fixation is sought. The dome screw may then be inserted into the central screw hole.

The liner is then positioned and impacted, and a clean small swab placed in the cup prior to proceeding with femoral preparation.

Acetabular screw holes (uncemented cups)

Acetabular screws may be placed in uncemented cups to augment fixation. The accuracy and safety of drilling and inserting trans-acetabular screws is paramount, and a thorough knowledge of the structures at risk is required when undertaking this.

Wasielewski and colleagues first described the concept of the quadrant system to help guide surgeons in placing trans-acetabular screws [69]. The quadrants are formed by drawing a line from the anterior superior iliac spine through the centre of the acetabulum to the posterior fovea, forming acetabular halves. A second line is then drawn perpendicular to the first at the mid-point of the acetabulum, forming four quadrants (see figure 41). The posterior-superior and posterior-inferior acetabular quadrants contain the best available bone stock and are relatively safe for screw placement. At the sciatic notch, the superior gluteal vessels are at greatest risk, lying an average of 5 mm from the notch.

The anterior-superior and anterior-inferior quadrants should be avoided whenever possible, because screws placed improperly in these quadrants may endanger the external iliac artery and vein, as well as the obturator nerve, artery, and vein (see figure 42). The external iliac vein has been shown to lie within 7 mm of the anterior column of the pelvis at the anterior inferior iliac spine and within 4 mm at the acetabular dome [58]. The external iliac artery is at less risk due to its thicker intima and increased distance from the bone. It lies within 10 mm of the bone at the anterior inferior iliac spine and within 7 mm at the acetabular dome. The obturator vessels also are at risk, lying fixed within 1 mm of the bony surface at the quadrilateral surface, with their only protection being the interposition of the obturator internus muscle.

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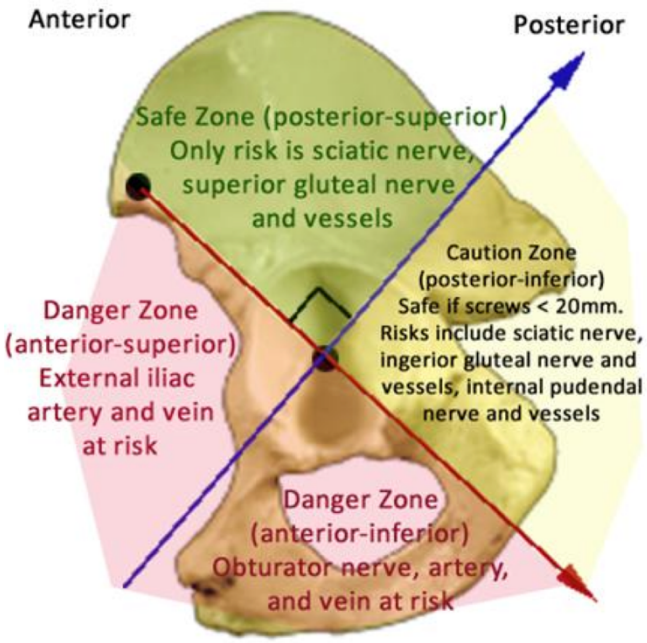


Figure 41: Left hemi-pelvis demonstrating the four quadrants, and the location of the posterior-superior 'safe zone' for screw placement in THR

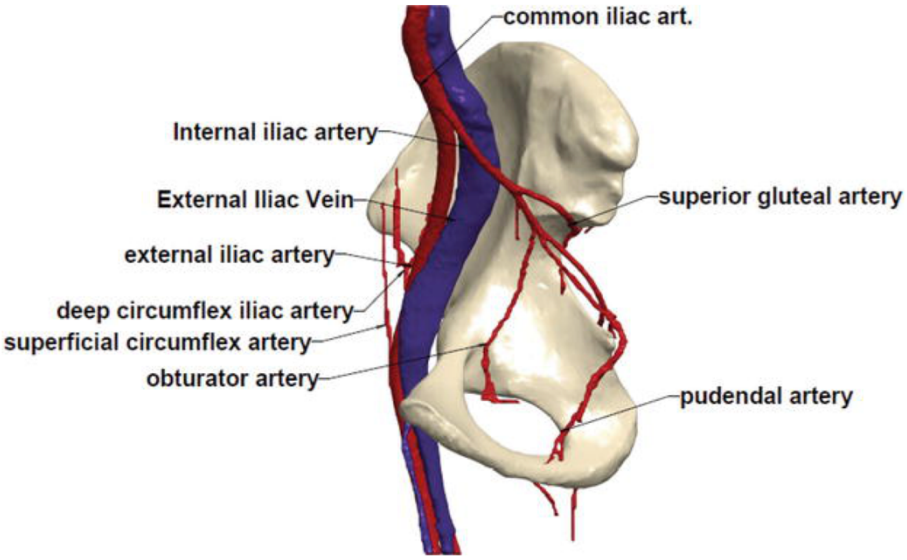


Figure 42: Right hemi-pelvis (medial view) demonstrating the location of the major vessels around the hip joint [70]

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Drill holes (cemented cups)

A step drill may be used to create holes around the inner periphery of the bony acetabulum prior to cementing. These holes increase cement penetrance and cup stability. A total of 6-10 drill holes are recommended.

Avoid the medial wall of the acetabulum, as this is thin and penetration risks intra-pelvic injury and cement extrusion. Also take care to avoid the danger quadrants listed above, namely the anterior-inferior and anterior-superior quadrants. The only possible exceptions to this may be placing drill holes into the pubis (antero-inferiorly) if you are certain of its location, and ischium (posterior-inferiorly). Drill holes may safely be placed in the superior and superior-posterior acetabular dome.

A pair of forceps can be used to probe the holes and ensure that the medial wall has not been penetrated. If this has occurred then packed with these should be packed with a plug of autologous bone graft harvested from the excised femoral head.

Cemented cup trialling, sizing & positioning

For the Stryker® Exeter Contemporary™, the cup size refers to the outer diameter of the cement spacers, and includes a 2-3mm cement mantle. Other cemented cup systems may not include the size of the cement mantle, and the surgeon should be aware of the guidance for the specific prosthesis used. For example, the Corin® Cenator™ cemented cup should be 4mm smaller than the diameter of final reamer used (e.g. a 44mm cup for the final reamer size 48mm). When assessing size and positioning of the cup the trial flange may be cut to check that it fits comfortably with room for at least a 2mm circumferential cement mantle. We recommend cutting and using the trial flange along with the trial cup mounted onto the introducer to template the shape required before the definitive component is chosen and prepared. When the definitive acetabular cut has been cut to measure, it should be mounted on the introducer in the correct position. The introducers have anterior and posterior, or left and right marking on them to assist with correct positioning.

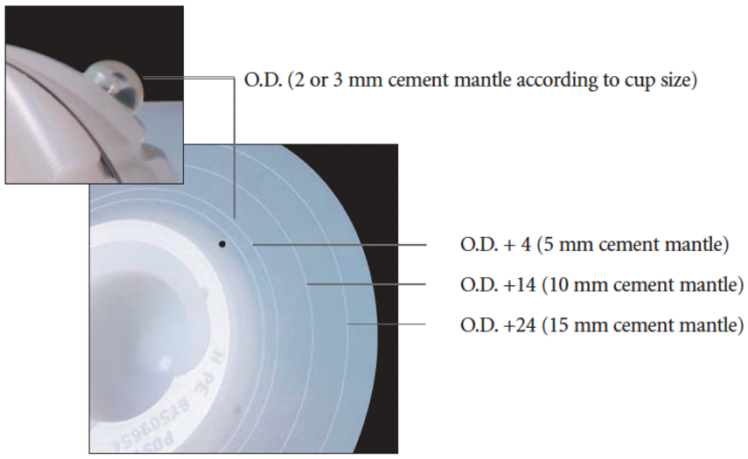


Figure 43: Markings on the flange of the Stryker® Exeter Contemporary™ cup used to indicate cement mantle thickness

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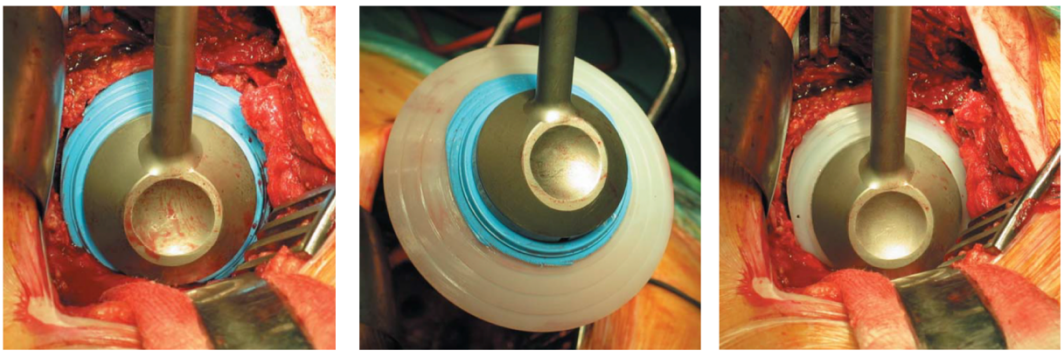


Figure 44: Sequence of cemented cup templating and preparation

Left: **Templating trial cup and trial flange (blue flange) on introducer**

Middle: **Trial flange overlying definitive cup allows this to be cut to size**

Right: **Definitive cup positioning on introducer**

Cementing technique and cup implantation

Pulsed lavage should be used to clear blood and debris, and a clean dry swab placed into the acetabulum prior to cementing. Some surgeons use swabs moistened with hydrogen peroxide, with a clean dry swab placed over the top with pressure applied.

A sucker-aspirator may be used whilst cementing an acetabular cup. The tip of this should be placed in the posterior column of the pelvis underneath the gluteus medius muscle and at least 1cm proximal to the acetabular rim in order to avoid iatrogenic fracture. Suction should only be attached to this device immediately before bone cement is inserted and pressurised in the acetabulum, otherwise it risks causing significant blood loss.

The cement may then be mixed and the timer started. When the cement has entered the working phase, which is signalled by 'scrotalisation' of its surface, a ball of adequate size to fill the acetabulum may be inserted and pressurised with correct size pusher for up to 4-6 minutes following initiation of mixing. This time is dependent upon the theatre environment (temperature, humidity etc). If using the suction aspirator this should be disconnected after the first minute of pressurisation. Any cement escape around the periphery should be removed.

Following pressurisation, the surface of the cement is padded dry and the cup is introduced. The cup should be placed from infero-medially in a slightly closed position to supero-laterally during positioning. This ensures medialisation of the cup and reduces cement escape into the obturator foramen. Axial pressure on the cup is applied with the pusher whilst the cup is being positioned. The handle of the lateral cup introducer should end up perpendicular to the long axis of the patient to achieve a 45° inclination. The version of the cup can be assessed as the relationship between the long axis of the patient and handle of the introducer, which can be rotated in order to achieve the desired version. The aim is to achieve 10-20° anteversion of the cup.

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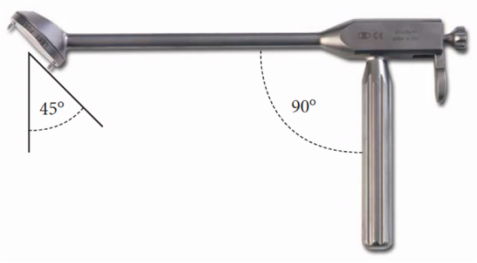


Figure 45: Stryker® Exeter Contemporary™ lateral cup introducer

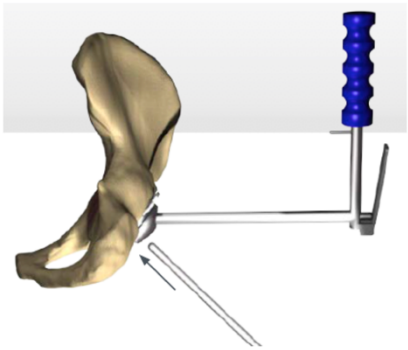


Figure 46: Corin® Cenator™ acetabular cup introducer and pusher

When the desired position has been achieved then introducer is gently removed using the trigger mechanism on the introducer, and the correct size ball pusher (e.g. 28mm or 32mm) applied to the cup in order to maintain firm pressure as the cement cures. Take care not to displace the cup positioning during removal of the introducer. Any extruded cement may be removed around the periphery of the cup whilst the cement is still doughy.

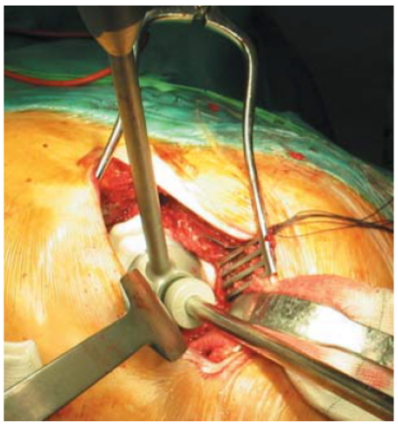


Figure 47: Insertion of cemented acetabular cup

Note the introducer is vertical to the floor and the ball pusher is guiding positioning and pressurisation

A clean small swab should then be placed in the acetabular cup prior to proceeding with femoral preparation.

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Femoral exposure, preparation & implantation

Femoral exposure

Posterior approach

When utilising the posterior approach to the hip, the femur is best visualised with the leg internally rotated, flexed, and slightly adducted [61]. The long axis of the tibia should be placed perpendicular (vertical) to the floor with the foot pointing upwards. This will aid in femoral preparation and determining component positioning (version and varus/valgus). Blunt Hohmann retractors or specialised femoral elevators may be placed underneath the gluteus medius muscle onto the antero-lateral border of the greater trochanter in order to reflect the muscle out of the way and raise the femur out of the wound slightly. This will facilitate visualisation prior to femoral preparation and component positioning.

Direct lateral approach

When utilising the direct lateral approach to the hip, the femur is best visualised with the leg externally rotated, flexed, and slightly adducted with the foot placed in a sterile bag on the contralateral side of the table in a 'figure of four' position. In this position the long axis of the tibia should be placed perpendicular (vertical) to the floor with the foot pointing downwards. This will aid in femoral preparation and determining component positioning. Again, blunt Hohmann retractors or specialised femoral elevators may be placed underneath the posterior border of the greater trochanter in order to raise the femur out of the wound slightly, which will facilitate visualisation prior to femoral preparation and component positioning.

Femoral neck osteotomy

The level of the femoral neck osteotomy may be templated pre-operatively. This is particularly important when using collared or uncemented femoral stems as the level of the osteotomy effectively determines the leg length. A neck resection guide is provided on many uncemented stem surgical trays, such as the Corin® Trifit™, which provide additional intra-operative guidance as to the level of the femoral neck osteotomy.

When using collarless cemented implants such as the Corin® Taperfit™, or Stryker® Exeter V40™ the level of the femoral neck osteotomy is less critical, however it is advised that it is not made so low as to leave all three laser etched markings on the prosthesis proud of the cement mantle. This would not provide an adequate proximal support for the prosthesis. In most individuals an appropriate level of neck resection lies along a line drawn from a point medially mid-way between the upper margin of the lesser trochanter and the inferior aspect of the head. (point A in figure 48), to a point laterally at the base of the neck (point B in figure 48). This is usually a fingers breadth above the lesser trochanter aiming towards the piriformis fossa in lateral aspect of the femoral neck.

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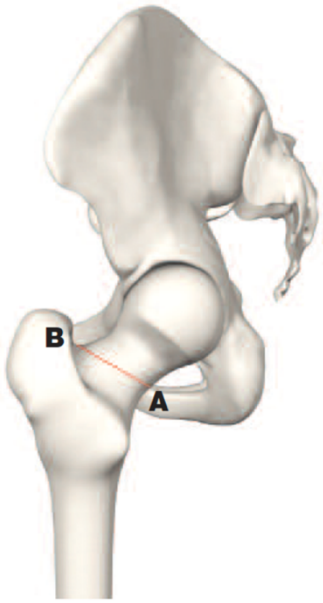


Figure 48: Recommended position of the femoral neck osteotomy for a cemented stem

Selection of a femoral component

Femoral stems may have modular or fixed neck shaft angles (NSA), offsets, and lengths.

For example, the Stryker® Exeter V40™ cemented stem has a fixed NSA of 125º, and options of 30mm (CDH), 33mm (CDH), 35.5mm (CDH), 37.5mm, 44mm, and 50mm offsets, with a standard length of 150mm. Whereas the Corin® Trifit™ uncemented stem has a fixed NSA of 130º, and length and offset increases along with the size of the broach used, from stem length 110mm with standard offset 35.5mm in the size 1 stem, to 130mm and 40.8mm in size 11 stem respectively. The Trifit™ is also available with either standard (32.4mm) or lateralised (37mm) neck lengths.

This variability makes it critically important for surgeons to be familiar with the equipment they will be using, and pre-operative planning again helps to predict in advance what components are likely to be required.

Most implants have the options of extended necks on the modular heads (For example, +/-4mm in the Stryker® Exeter V40™. Changing the neck length also affects offset and length (Pythagorean theory). Changing the neck length in the Stryker® Exeter V40™ system has the following effect on femoral offset and leg length:

Neck	Femoral Offset	Leg length
-4mm	**-3.27mm**	**-2.29mm**
0	**0**	**0**
+4mm	**+3.27mm**	**+2.29mm**

As we outlined in the section on pre-operative templating, the neck-shaft angle (NSA) affects the FO. The offset and depth of the femoral stem must therefore be accounted for in combination.

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Coxa VARA

In patients with coxa vara, using a femoral component with a standard NSA and offset has the effect of reducing FO and causes inadequate tensioning of the hip abductors.

In order to recreate adequate abductor muscle tension, either:

1) A femoral component with a standard NSA and normal offset can be inserted to a lesser depth if cemented, or a higher neck cut made if using an uncemented prosthesis. However, both of these options have the effect of increasing leg length in order to adequately tension the abductors.
2) A femoral component with a standard NSA and extended offset can be used, which will maintain the previous leg length and adequately tension the abductors.

Coxa VALGA

In patients with coxa valga, the position of the femoral neck osteotomy and depth of component implantation is more critical.

If using a femoral component with a standard NSA and offset then inserting it to the depth you would for a patient with a NSA within the normal range would result in an increased FO, and shortening of the leg length.

In order to recreate normal hip biomechanics using a femoral component with a standard NSA and offset, then it is important to leave the stem slightly proud, either by not inserting as deep when using a cemented prosthesis, or by performing a high femoral neck osteotomy when using an uncemented prosthesis. A minus head, or shorter neck if modular systems are available should also be considered.

Femoral canal preparation and implantation for cemented stems

A hollow box chisel is used to open the metaphysis of the proximal femur. This is positioned at the postero-lateral corner of the femur at the level of the neck cut, and just medial to the overhang of the GT. Placing the box chisel any more medially may result in remainder of the femoral preparation and stem insertion in a varus position. If using a cemented stem, a Volkmann's spoon or curette may also be used at this stage to remove a little cancellous bone within the greater trochanter to allow cement coverage and penetration in this area.

The taper pin reamers (usually two) may then be sequentially passed down the centre of the femoral canal, using gentle clockwise rotation on the handle in order to cut through the cancellous bone (see figure 49). Again, pressure should be applied in the lateral (valgus) direction at the proximal femur to open the proximal lateral cortex. The surgeon should place their contralateral hand on the patients knee to provide a guide for the direction of passage of the taper pin reamers down the long axis of the femur, which should be aimed at the intercondylar area of the distal femur.

If passage of the taper pin reamers is difficult, this is an indication that either the direction of passage is incorrect (usually too varus), or that the femoral canal is narrow distally. This should have been identified in the pre-op templating. Dorr Type A femurs have particularly thick cortices that begin at the distal end of the lesser trochanter and thicken quickly, producing a funnel shape and a narrow diaphyseal canal. This morphology may limit the passage of a standard femoral stem, especially when accounting for an adequate cement mantle. If this situation is encountered and has not been anticipated pre-operatively, then consideration should be given for using a cemented short stem. If this is not available, and on very rare occasions, a

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guidewire may be passed down the femoral canal and flexible reamers used to enlarge the endosteal cavity, such as those used in the preparation for in intra-medullary femoral nailing system.

Manual lavage of the femoral canal using a bladder syringe and saline should be performed prior to commencing with femoral rasping.

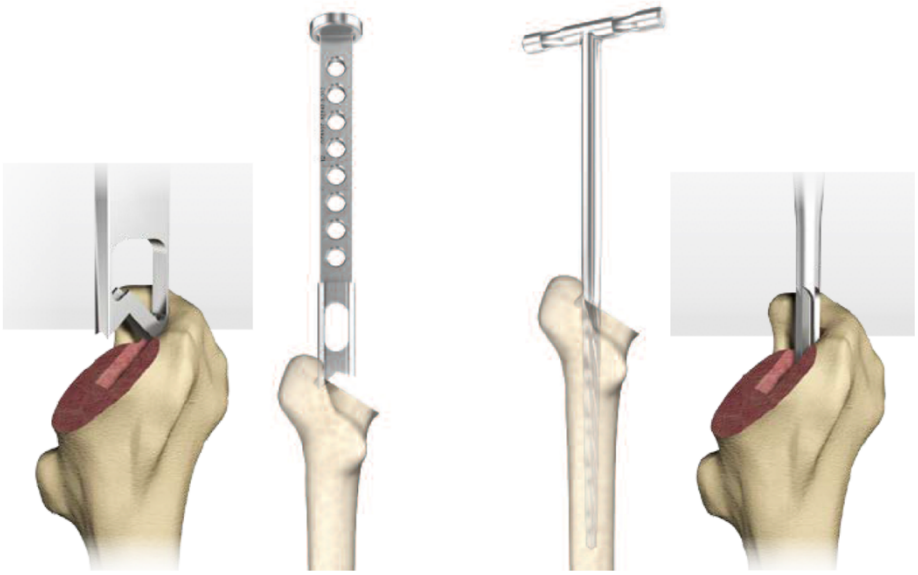


Figure 49: Box chisel and taper pin reamers used in femoral preparation

Femoral broaching/rasping

At all stages of femoral broaching attention should be paid to the alignment of the broach in all planes. This includes the varus/valgus (coronal), version (axial), and antero-posterior (sagittal) positioning. The smallest broach should be mounted onto its introducer/ broach handle and initially used without the mallet to manually work into the lateral proximal femoral cortex (see figure 50). This is to allow the straight passage of the femoral stem, and reduces the chance of varus insertion. Once the broach is unable to be advanced manually the mallet is used to impact the end plate of the broach handle to advance the broach down to the desired level.

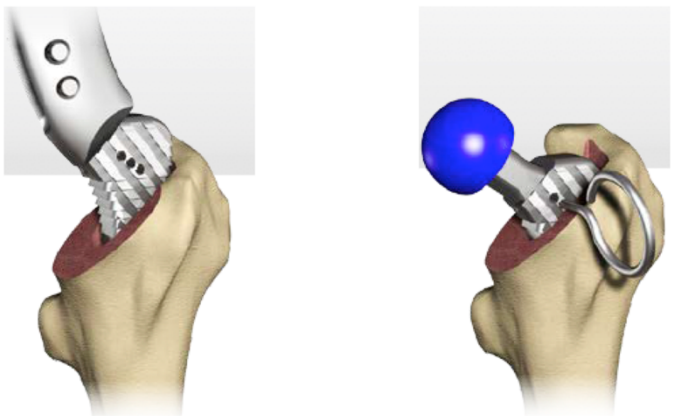


Figure 50: Insertion of femoral broach into lateral proximal femur (left)

Pin placed in femoral broach for trialling (right)

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Most cemented stem systems will contain modular broaches with fixed offset necks, therefore broaches of the anticipated required offset should be used for femoral preparation prior to the trial reduction. Sequential broaching using increasing sizes is performed in a similar fashion to the initial broach until a change in note is observed on impacting with the mallet and the broach is unable to be advanced. This indicates that broach is contacting the endosteum at a level within the canal, and no further force should be applied as it risks intra-operative fracture. The size of the final broach which is able to be passed to the correct depth is used to select the definitive stem size, and should be similar to the size estimated from pre-operative templating. The broaches are slightly bigger than the corresponding sized stem, which will leave room for an adequate circumferential cement mantle. The aim is to leave 2mm of strong cancellous bone circumferentially around the endosteum into which cement can be pressurised. If passage of a particular sized broach is difficult, then many theatres will keep a range of sterile 'smooth' femoral stem trials, which may be used to assess if passage of a stem is possible, despite the corresponding broach not being able to fit fully down the femoral canal.

A note should be made of the position of the hole on the anterior broach in relation to the calcar prior to a trial reduction. Following a satisfactory trial reduction, the level of the hole can be marked on the calcar using the diathermy, which will serve as a reminder as to the desired depth of stem insertion.

The introducer should then be removed and a standard head applied to the trunnion of the broach. The hip is then reduced and an assessment of leg lengths, soft tissue tension, range of motion and stability is performed. Details of these assessments will be covered in subsequent training session. Any adjustments may then be made according to the findings. If a satisfactory pre-operative plan for stem positioning has been well executed then usually the first trial will often reveal a satisfactory leg length and offset. However, in general the following principles apply to addressing these possible findings:

Leg too long: insert broach further down the femoral canal (may have to downsize the size of the broach). Trial minus size neck (reduces femoral offset and leg length concomitantly) if only slightly too long.

Leg too short: plan to insert stem to a lesser depth and mark accordingly on the calcar using diathermy. When using a cemented stem system, a pin may be placed in one of the calcar holes on the femoral broach to block the depth to which it can be inserted when performing a further trial reduction (see figure 50). Trial plus sized neck (increases femoral offset and leg length concomitantly) if only slightly too short.

Inadequate soft tissue (SER or Abductor) tension: increase stem offset, or trial a plus-sized neck. Reduce depth of stem insertion leg length if also found to be short.

Soft tissues overly tight: reduce offset of stem or trial a minus sized neck. Consider soft tissue releases if contractures suspected (e.g. anterior capsule release or reflected head of rectus femoris). Increase depth of stem insertion if leg length also found to be long.

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Cemented stem implantation & positioning

It is good surgical practise to change gloves before handling any prosthesis prior to insertion.

The surgical assistant's role is to maintain the position of the leg during stem insertion, which is covered in femoral exposure.

The optimal stem position should be known, and marked following the trial reduction and assessment.

The femoral canal cement restrictor (plug) requires sizing and inserting prior to cementation. This is performed by starting with the smallest sized femoral canal sizing sound and passing it down the femoral canal. Sequentially increasing sized sounds are then passed until reaching the first one that jams in the femoral canal when its landmark (corresponding to the stem length chosen) is at or just below the tip of the greater trochanter. This sound indicates the size of distal cement restrictor that should be used. The chosen sized cement restrictor plug is then mounted onto the introducer and gently inserted to the desired depth. Most introducers will have marks corresponding to the marks on the femoral stem, which serve as an aid to the depth of insertion of the cement restrictor. Inserting the cement restrictor to the level of the planned stem depth using the introducer allows for a 1cm cement mantle distal to the tip of the stem.

The chosen stem should be mounted onto the introducer and the centraliser applied to the tip of the stem. Smooth centralisers are used for cement restrictor sizes <10mm, and fluted centralisers are used for cement restrictor sizes >10mm. These should be placed onto a clean swab in an easily accessible position. The scrub nurse can be asked to mix the cement whilst the final femoral preparation steps are taking place.

Pulsed lavage and a mechanical brush should be used to clear the femoral canal of blood and debris prior to cementing. This provides a clean surface of the cancellous bone to allow interdigitation of the bone cement following its introduction and pressurisation. A suction catheter tube is placed down the canal and attached to the suction, whilst the canal is packed with sterile ribbon gauze using a small femoral sound. Some surgeons advocate moistening the ribbon gauze with hydrogen peroxide. These steps prevent the canal from filling with blood.
The filled cement gun with long nozzle should have a half-moon seal applied to its proximal end in order to allow pressurisation following cement insertion. When the cement has 'scrotalised' the ribbon gauze and suction catheter are removed, and the nozzle is advance down the canal to the end and the cement smoothly and progressively inserted in a retrograde fashion by squeezing the trigger of the gun (see figure 51). The pressure of the cement filling the canal should facilitate the gradual withdrawal on the nozzle. Continue until the entire canal is filled with cement. At the stage, any remaining cement within the nozzle can be pushed back into the chamber by unlocking the guns mechanism and the scrub nurse placing an inner rod back up the nozzle. The long nozzle is then snapped or cut off, but the half-moon seal retained around the stump of the proximal nozzle. This is then placed back into the proximal femoral metaphysis with the half-moon seal firmly around the calcar. Pressurisation of the cement mantle is then performed by slowly but firmly and constantly squeezing the trigger until cement, blood, or fat is seen exuding from around the seal. When this is seen the nozzle may be removed, and a little further cement injected into the defect left by the seal. The visible cement is then padded dry using a clean dry swab.

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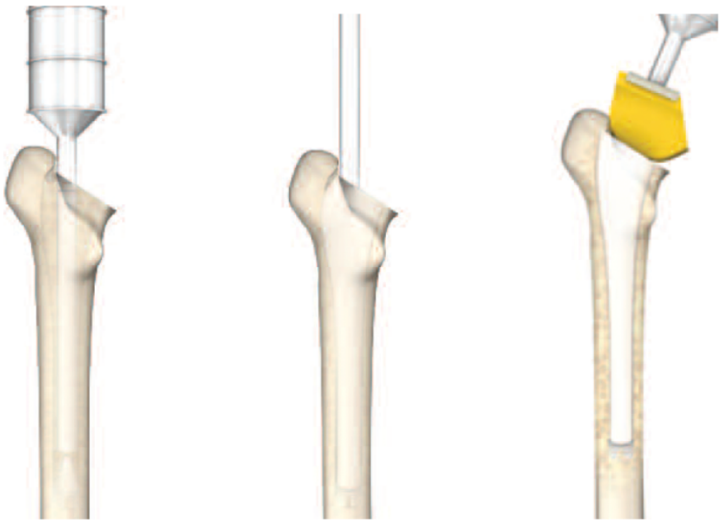


Figure 51: Steps of femoral cementing

Left: Long nozzle placed all the way down the femoral canal to the level of the cement restrictor

Middle: Femoral canal filled in retrograde fashion

Right: Cement mantle pressurised with the use of the half-moon seal and short nozzle

The femoral stem loaded onto its introducer is then picked up and aligned ready for insertion. The surgeon's contralateral thumb should be placed over the calcar during stem insertion in order to boost pressurisation during stem insertion and also prevent cement escape and varus stem positioning. A cement 'horse collar' may also be used to prevent cement escape and maintain cement pressurisation during the stem insertion. The stem is then slowly advanced into the cement starting from a postero-lateral point and progressing in the correct version and alignment towards the mid-point of the distal femur as judged by the position of the perpendicularly held leg until it reaches the planned depth and alignment of insertion. At this point the stem introducer may be removed, and a femoral sound used to maintain the stems depth and prevent it from backing out by placing the tip of it onto the hole at the shoulder of the prosthesis.
Any excess cement may be cleared at this point and the stem should be held in this position until the cement cures. A residual blob of cement kept by the scrub nurse is usually kept for this purpose. The cement is adequately cured when the blade of a scalpel cannot be used to penetrate its surface around the stem.

A further trial reduction may be performed using the standard femoral head and neck, and any adjustments made (for example plus or minus sized neck) before the definitive head/neck is then impacted into position on the trunnion and the final hip reduction performed.

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Femoral canal preparation and implantation for uncemented stems

Whilst there are many similarities to preparing the femur for both a cemented and uncemented stem, a few important differences should be noted. For reasons explained previously, the neck cut and preparation for uncemented femoral stems is more critical than for collarless cemented stems.

For this reason, the majority of uncemented stem sets will contain a femoral neck osteotomy guide, such as the Corin® Trifit™ (see figures 52 and 53). This is a uncemented tapered femoral stem with metaphyseal hydroxyapatite coating. In this system, the femoral neck osteotomy guide is placed so that the long axis of the instrument is in line with the long axis of the femur. Using diathermy, a line is marked on the femoral neck at 50º to the long axis through the slot, and the osteotomy is performed along this marked line. The box chisel cut, taper pin reaming, and sequential broaching is performed in a similar fashion to a cemented stem, however at this stage a fan reamer may be used on power to smooth the femoral neck osteotomy at the level of the final broach (see figure 52).

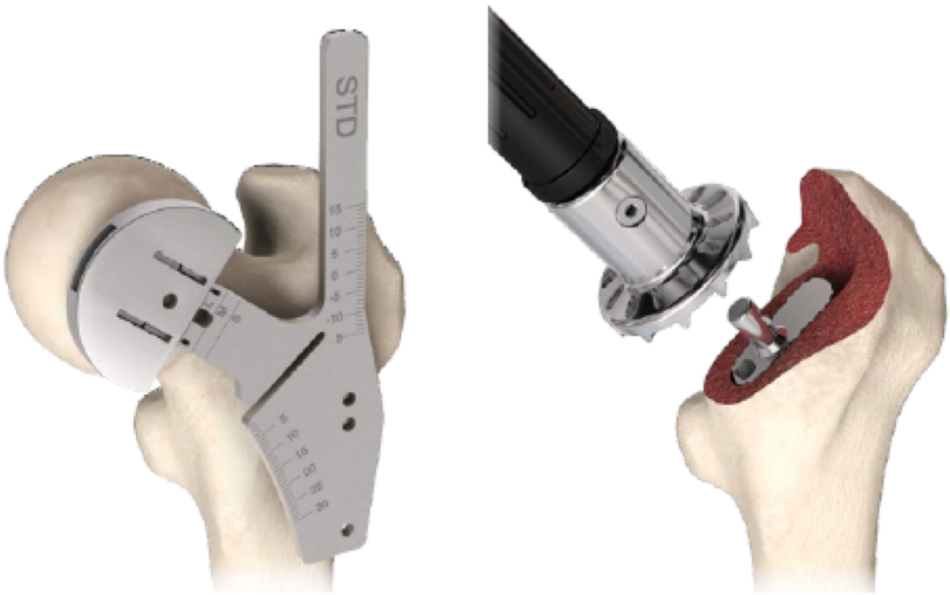


Figure 52: Examples of the Corin® Trifit™ femoral neck osteotomy guide and calcar reamer

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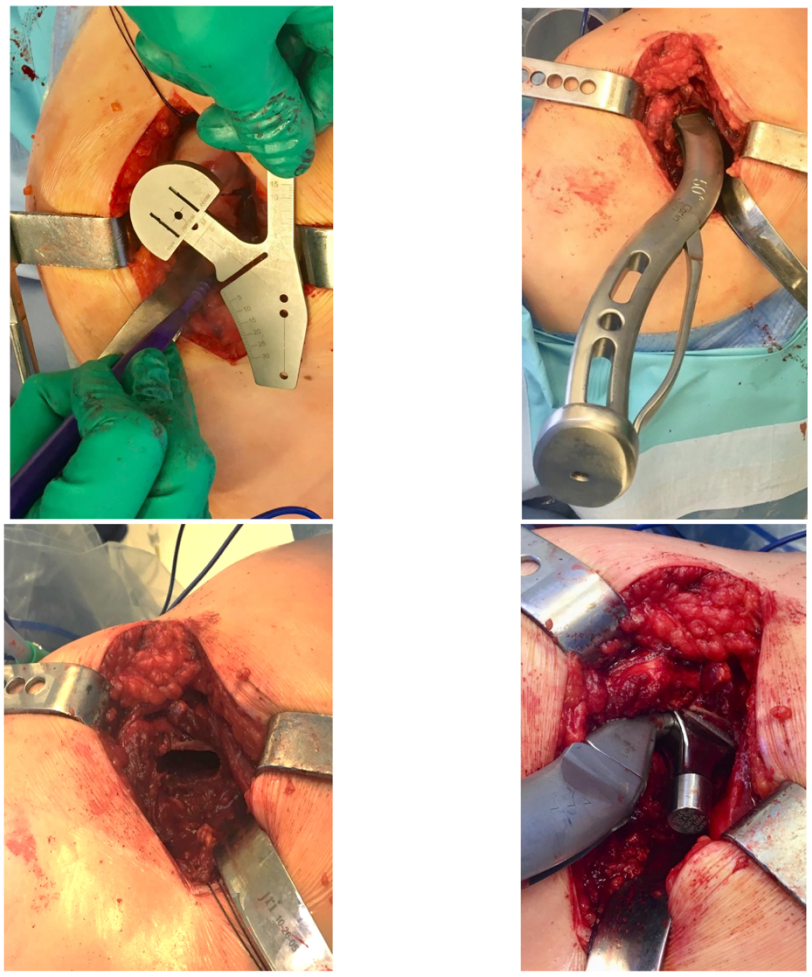


Figure 53: Intra-operative photographs of the neck osteotomy guide, broaching, and implantation of a Corin® Trifit™ uncemented femoral stem

Attach the appropriate head and neck trials to the final broach used after final preparations to the calcar and perform a trial reduction to assess stability, offset and leg length. If the leg has been lengthened so that it cannot be managed easily with the modular head/neck options, consideration should be given to modifying the neck resection, and repeating the broaching and calcar preparation.

Uncemented stem implantation

With the Corin® Trifit™ the final broach size indicates the definitive implant size, and the alignment (version and varus/valgus) cannot be easily changed during stem insertion as this is largely dictated during the broaching. Furthermore, although suctioning of the canal may be performed prior to stem insertion, lavage is not advisable. The selected stem may be inserted using its introducer and impacted into position. A further trial reduction may be performed using the standard femoral head and neck, and any adjustments made (for example plus or minus sized neck) before the definitive head/neck is then impacted into position on the trunnion and the final hip reduction performed.

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Reconstructing Hip Biomechanics, and Surgical Closure

The principles of hip biomechanics, parameters for their clinical and radiographical assessment, and the methods for accurately restoring them surgically during the steps of a primary THR have been outlined in weeks 1 to 3 of this course.

As previously mentioned, the accurate restoration of normal hip biomechanics during THR is known to result in: improved patient function & satisfaction; reduced incidence of complications such as dislocation; and increased longevity of the implants [2-7]. Contrary to this, component mal-positioning and mis-sizing may result in: excessive wear, instability & increased risk of dislocation; failure of fixation, leg length discrepancy, and poor functional outcomes.

The importance of accurately reconstructing hip biomechanics in order to achieve satisfactory patient outcomes following primary THR has also been highlighted in the Delphi Expert consensus. The results of this demonstrated that Consultant Orthopaedic Surgeons rank the assessment of leg length and hip offset as both being in the top 10 most important steps in terms of impact on patient outcomes, and both in the top 3 most difficult to teach trainee's how to perform. For these reasons, we have dedicated the final week of this course to describing in greater detail why these parameters are so important, and the possible methods that can be utilised to reconstruct hip biomechanics accurately. Finally, we will outline how to perform a secure surgical wound closure, which has been proven to reduce the risk of post-operative dislocation [63].

The following parameters of hip biomechanics must be considered pre-operatively and recreated intra-operatively in order to produce a satisfactory result for the patient following THR:

- Centre of rotation (COR) of the hip joint
- Femoral offset (FO) and acetabular offset (AO)
- Femoral neck version and neck-shaft angle (NSA)
- Acetabular inclination and version
- Leg length (LL)

The biomechanical and functional relevance of these parameters, and commonly used methods used to assess and recreate these intra-operatively will be addressed.

It should be noted that all intra-operative assessments of component positioning are influenced by:

- Patient positioning: lateral decubitus or supine
- Surgical approach: posterior versus direct lateral
- Anaesthesia: Regional Anaesthesia (RA) versus General Anaesthesia (GA).

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Centre of rotation (COR) of the hip joint

Accurately restoring the COR of the hip has been shown to reduce wear rates, improve stability and hip biomechanics [71-75]. The COR of a THR is largely determined by the placement of the acetabular cup. This can be described by the cup position vertically (height), horizontally (depth), and antero-posterior direction [48]. The vertical COR may be restored by placing the inferior margin of an appropriately sized acetabular cup at the level of the acetabular teardrop/ transverse acetabular ligament (TAL). The horizontal COR may be restored by placing the medial margin of an appropriately sized acetabular cup adjacent to, but not beyond the medial wall (true floor) of the acetabulum. Shao *et al* reported that the hip COR could be restored by placing the medial margin of the acetabular component about 2 mm to the lateral border of the ipsilateral teardrop [76]. Beverland *et al* have suggested that the hip COR may be restored by placing the acetabular component, which is no more than 4mm larger than the native femoral head, just deep to the plane of the TAL and labrum [47].

When templating for cases involving either acetabular, femoral or combined bone loss, the centre of rotation (COR) of both the acetabulum and femur will not lie at the same level. In these cases, the COR for both must be marked, and the perpendicular distance between these points against the inter-teardrop line can be used to estimate the anatomical LLD. Both the acetabular and femoral COR must be restored independently in order to recreate normal hip biomechanics and address any LLD.

Hill *et al* reported on the accuracy of a calliper-based technique to assist femoral COR restoration in both in-vitro models using sawbones (n=9), and post-operative CT-based analysis in patients (n=38) following primary THR [77]. The results of this study demonstrated that the femoral COR was predicted by the calliper to within 4.3mm (mean 1.6mm) for offset and to within 2.4mm (mean 0.6mm) for vertical height in the sawbones model; and to within 8mm (mean -1mm) and 14mm (mean 4mm) respectively in the post-operative CT analysis. Meermans *et al* reported on a technique whereby the first acetabular reamer used in preparation was the same size of the native femoral head [78]. Utilising this technique resulted in a more accurate restoration of the hip COR (horizontally and vertically) than the classical technique of reaming to the acetabular floor initially then expanding outwards. Similar findings for accurately restoring the hip COR using this technique were also reported in a CT-based study by Bonnin *et al* [79]. However, this technique has been shown to result in more uncovering of the acetabular component supero-laterally, and if not adequately anteverted then it may also lead to anterior overhang and resultant iliopsoas impingement [78]. A further CT-based study has demonstrated that using the tip of the GT as a surrogate anatomical marker for the femoral COR is unreliable and should not be used [80].

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Femoral offset (FO) and acetabular offset (AO)

FO represents the lever (or moment) arm through which the hip abductor muscles (gluteus medius and minimus) act to hold the pelvis level during both single leg stance, and throughout the gait cycle. Increasing the FO increases the both the tension on the hip abductors and the effective lever arm, and thereby reduces the force generation required to maintain the position of the pelvis.

Increasing FO during a THR creates a larger abductor moment arm, which may decrease the hips joint-reaction force [81]. Increasing FO has been found to and increase both the stability and range of movement of a THR [20, 82]. However, increasing the FO significantly beyond normal may have the detrimental effect of giving the patient a perception of a longer leg, due to excessive tension on the abductor muscles, and may also cause trochanteric bursitis and gluteal pain in up to 15% of patients [82]. Reducing the FO during THR reduces the abductor lever arm, and causes a limp, increased joint reaction forces, and increased risk of dislocation caused by a combination of inadequate abductor tension and impingement of the femoral neck on the acetabular rim on the extreme ROM [20, 83, 84].

A recent systematic review of case-control series has highlighted that the accurate restoration of FO in THR has been shown to reduce the wear rates of conventional ultra-high molecular weight polyethylene bearings (UHMWPE) [85]. Although there is also a theoretical benefit of reduced dislocation and aseptic loosening in THR with accurately restored FO, this was not demonstrated in this systematic review.

Failure to recreate the normal FO may result in patient dissatisfaction, component instability & increased wear, weakness, limp, and reduced range of movement of the hip [4, 20, 83, 84, 86, 87]. Studies have reported that a decrease of 15% in FO results in weakness of the abductors and an alteration in gait pattern following THR [74, 88]. Review papers have demonstrated that surgeons are more likely to inadvertently reduce the FO rather than increase it [6]. FO is difficult to precisely measure using standard pelvic radiographs, which usually underestimate the FO by a mean value of 3.2mm, and studies have suggested that CT scans are the gold standard in accuracy of FO measurement [89].

Intra-operative techniques for restoring FO

1) Assess the soft-tissue tension of the abductors or SER's following trial reduction. When using a posterior surgical approach to the hip, the piriformis tendon should be routinely tagged prior to division close to its insertion on the posterior lateral femoral neck. Following a trial reduction of the THR, the operative leg should be placed back into the position it was in at the start of the operation, lined up with the inferior leg. The tagged piriformis tendon may then be brought up to approximate with its insertion point by the surgeon. If the FO has been restored accurately then the end of the piriformis tendon should lie flush with its original point of insertion. If the FO is reduced, the end of the tendon will pass beyond this point, and if the FO is too high the surgeon will not be able to reach this point with the end of the tendon. The tension of the piriformis tendon will also be affected by the overall leg length, which will need to be addressed concurrently.

2) Smooth femoral stem trials or broaches (with modular necks attached if applicable) of known fixed offset, for example 37.5mm, 44mm, or 50mm in the Stryker® Exeter V40™ may be used to template the FO of the native femur intra-operatively. This should take place following surgical dislocation of the hip and prior to performing the neck osteotomy. The chosen smooth trial stem or broach should be placed over the anterior proximal femur in line with the shaft distally and estimated position proximally, and the centre of the neck/trunnion noted in relation to the centre of the femoral head. The offset may then be adjusted in

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order to place the centre of the neck/trunnion in the COR of the femoral head in order to recreate the native FO. Broaching using this templated offset may then commence prior to performing a trial reduction.

Intra-operative techniques for restoring AO

1) They key to restoring AO is to accurately position a well sized acetabular cup. Pre-operative templating will help determine the optimal position and size, however intra-operatively certain anatomical landmarks should be identified and used as reference points to guide the surgeon in cup placement. The most important of these landmarks are the transverse acetabular ligament (TAL), and the medial wall (true floor) of the acetabulum. The TAL marks the inferior most position for placement of the acetabular cup, and also provides a guide to native acetabular anteversion. The medial wall of the acetabulum may be identified by adequately removing any soft tissue within the cotyloid fossa, prior to medial reaming (deepening) of the acetabulum using the starter reamer. The medial wall of the acetabulum represents the medial most point for acetabular cup placement. The identification and use of these inferior and medial landmarks during acetabular preparation and cup placement will help restore the normal AO.

2) Avoid over-medialising the cup. This may be caused by breaching the true floor of the acetabulum during reaming. If this happens, then small defects with an intact medial membrane may be filled with autologous bone graft. Larger defects may require the use of a 'Mexican Hat' or wire mesh to plug the medial hole prior to bone grafting. Over-medialisation of the cup reduces AO and global offset, which may only be balanced by increasing the FO by using an extended offset stem or plus sized head/neck. However, using an extended offset stem or plus sized head/neck in this situation will also lengthen the leg (according to Pythagorean theorem). In order to mitigate for any leg lengthening in this circumstance consideration should be given to placing the stem slightly deeper into the canal if using a cemented stem, or performing additional calcar reaming if using an uncemented stem.

Femoral neck version and neck-shaft angle (NSA)

Femoral neck version is known to affect FO, with an increased femoral anteversion decreasing the FO [21]. The femoral neck-shaft angle (NSA) is also known to affect FO, with a varus NSA (Coxa Vara) increasing, and a valgus NSA (Coxa Valga) decreasing the FO. This should be noted and planned for during pre-operative planning and templating. Most femoral stems will have a fixed NSA, for example of 125º in the Stryker® Exeter V40™ cemented stem. However, these vary across manufacturers. A decrease in FO is often due to a stem NSA greater than the native value [20].

In patients with Coxa Vara, the following considerations should be given when selecting a femoral component in order to recreate FO and leg length:
1) Using an extended offset prosthesis
2) Inserting the stem deeper into canal if using a cemented stem
3) Performing a low femoral neck osteotomy if using an uncemented stem

In patients with Coxa Valga, the following considerations should be given when selecting a femoral component in order to recreate FO and leg length:
1) Using a standard or reduced offset prosthesis with a minus sized head
2) Leaving the femoral stem slightly proud if using a cemented stem
3) Performing a high femoral neck osteotomy if using an uncemented stem

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Acetabular orientation (inclination and version)

Definition of inclination and version, the importance of patient positioning, and consequences of component mal-positioning

Patient positioning, in particular pelvic orientation is critical for achieving accurate component placement, especially of the acetabular cup. Bony and soft tissue landmarks may be difficult to accurately assess with patients positioned in a lateral decubitus position [90]. The orientation of an acetabular prosthesis may be described by its inclination and version, and this can be assessed anatomically, radiographically, or operatively [91]. The operative acetabular anteversion (OA) is defined as the angle subtended between the longitudinal axis of the patient and the acetabular axis in the sagittal plane. The operative acetabular inclination (OI) is the angle subtended between the acetabular axis and the sagittal plane (see figure 54).

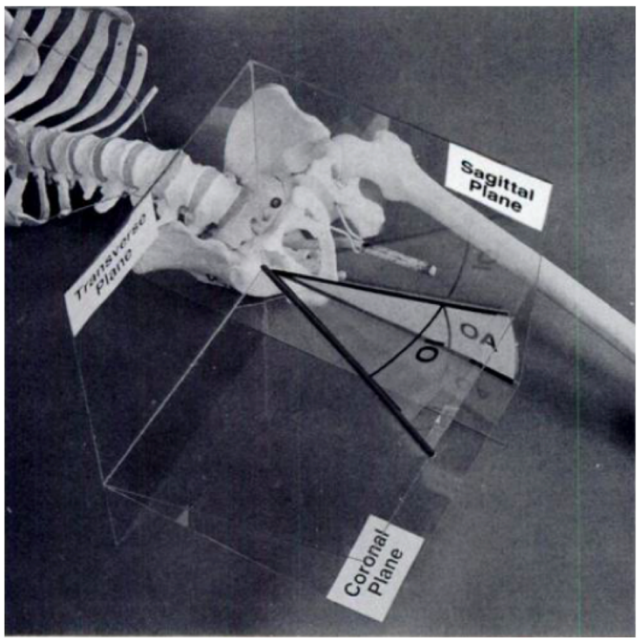


Figure 54: Definition of operative anteversion (OA) and inclination (OI)

OI is usually less than radiographic inclination (RI), as RI increases with increasing anteversion. The relationship between operative and radiographic acetabular cup orientation was investigated in a study by Grammatopolous *et al* [92]. The results of this study identified a mean difference between OI and RI of 5º (SD 5º), and between OA and RA of -8º (SD 8º). The authors concluded that in order to achieve the desired radiographic orientation, surgeons should aim to implant the acetabular component 5º less inclined, and 8º more anteverted than their target. A further study comparing the values of OI to the RI in a series of 60 patients undergoing primary THR in the lateral decubitus position via the posterior approach, and reported that the mean post-operative RI was 13º greater than the photographed OI [93]. The authors suggested that when performing THR through a posterior surgical approach with patients in the lateral decubitus position the upper pelvis adducts (sag), thus reducing the apparent operative inclination (AOI) (see figure 55 B). Surgeons using this approach must therefore aim for a lower OI (35º) in order to achieve an acceptable RI (45º) [93].

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As OI is referenced off the patient's true sagittal plane, an awareness and understanding of the patients position in theatre is critical in order to accurately recreate their native OI. Most surgeons will use the theatre floor or surgical table as a surrogate reference of the patient's sagittal plane when orientating the acetabular cup, however this does not take into account any pelvic adduction or tilt on table. In the lateral decubitus position, when the superior pelvis adducts the sagittal plane of the pelvis is no longer in line with the theatre floor. In this situation the apparent operative inclination (AOI) will be less than the true OI (see figure 56), and this must be accounted for. The importance of pelvic adduction when determining acetabular component in order to achieve a target RI has been highlighted in a series of papers by O'Neill *et al* [48, 94]. In one of their studies a marker pen and spirit level was used to draw transverse pelvic lines (TPL's) on patients backs in theatre (see figure 55) and the table was positioned either horizontal (figure B), 7° head down, or in a patient-specific position based on the correction of the pelvic adduction using a plumb-line (figure C). They reported that patient-specific position resulted in the smallest deviation in the achievement of a target RI of 42°. The authors state that failure to ensure that the pelvic sagittal plane is horizontal during THR is by far the greatest source of error with respect to RI.



A **B** **C**

Figure 55: The effect of patient positioning on pelvic adduction (sag or tilt)[48]

A: TPLs drawn in sitting position with horizontal operating table.
B: TPLs in lateral decubitus position with horizontal operating table. Upper hemipelvis appears adducted.
C: Operating table position adjusted with aid of plumb line in order to obtain vertical TPLs and obtain neutral pelvic position.

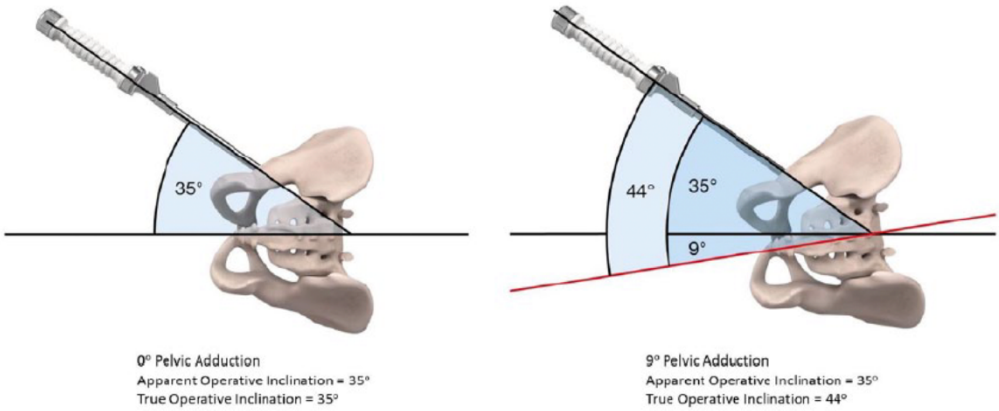


Figure 56: Difference between the apparent and true OI without (left) and with (right) accounting for on table pelvic adduction (sag).

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Mal-positioning of the acetabular cup is a known risk factor for impingement, instability, dislocation, and increased wear rates in THR [87, 95-98]. In a seminal paper Lewinek *et al* reported that the dislocation rate for THR with acetabular cup orientation with radiographic anteversion (RA) of 15 +/- 10 degrees and radiographic inclination (RI) of 40 +/- 10 degrees was 1.5%, while outside this "safe" range the dislocation rate was 6.1% [97]. The 'Lewinek safe zone' of cup positioning was born out of the results of this study, however subsequent studies have highlighted scientific flaws in the methodology and conclusions used in the Lewinek study [47, 98]. A recent CT-based study investigating the role of acetabular component positioning on hip stability reported that 32% of unstable hips were located in the Lewinek safe zone, and that the safe zone for OA is narrower than it is for OI [99]. The authors reported that anteriorly unstable hips had higher OA and tilt-adjusted OA, posteriorly unstable hips had lower OA and tilt-adjusted OA, and a new safe zone of 43º+/- 12º inclination with 31º +/- 8º of tilt-adjusted anteversion was recommended. Other studies have also highlighted a high percentage of dislocations of THR with components placed within the Lewinek 'safe zone' [100]. An increased risk of acetabular component mal-positioning has also been associated with lower-volume surgeons and patients with a higher body mass index (BMI) [101]. An in-vitro study using a sawbones hemipelvis model by Grammatopoulos *et al* investigated surgeon's accuracy in achieving their desired acetabular component [102]. A large variation in cup orientation angles were noted, however overall surgeons were found to over-estimate OI and underestimate OA. A further *in-vivo* study investigating acetabular cup orientation in THR using a freehand technique reported a tendency for both surgeons and surgical trainees to underestimate inclination and anteversion of the component [103].

The Transverse Acetabular Ligament (TAL)

Archbold *et al* described the use of the TAL as an intra-operative anatomical landmark to help guide the version of acetabular component positioning [47, 104]. The TAL is patient-specific and independent of pelvic tilt, which may be significantly affected by patient positioning for THR [47]. The TAL has been used to guide the height, depth, and version of the acetabular component, but should not be used as a guide to acetabular inclination [47]. Using the TAL reportedly reduced the incidence of post-operative dislocation to 0.6% in a series of 1000 consecutive THR's using neutral liners and 28mm heads. Using the TAL and posterior labrum as intra-operative anatomical landmarks for cup orientation, one study has shown that this reduce the incidence of serious cup mal-positioning outside the Lewinek safe zone to 13% [105]. However, this has not been proven to result in a better functional range of movement, or reduced risk of impingement. Another study highlighted that the TAL was only able to be identified intra-operatively in 47% of patients undergoing THR, and that cup orientation was no more accurate for cup positioning than free-hand technique [106].

The Posterior Acetabular Wall (PAW)

A more recent study investigated the use of the PAW as a guide for cup placement in THR performed through a posterior surgical approach and using either 32mm or 36mm heads in a cohort of 200 patients [107]. The rationale for this is that the TAL is a continuation of the posterior labrum, and therefore the PAW is a useful adjunct to and surrogate landmark for the TAL, which is visible on radiographs. In this study the PAW was graded as normal, prominent, or deficient by determining its relationship with the femoral COR on a pre-operative plain AP pelvis radiograph [108]. If the femoral COR was within 2mm of the PAW this was graded as normal, if it was >2mm medial to the PAW this was graded as prominent, and if it was >2mm lateral to the PAW was graded as deficient. For patients with a normal PAW (77%) the acetabular cup was placed flush with this intra-operatively, if the PAW was deficient (14.5%) the cup was placed slightly proud, and if the PAW was prominent (8.5%) the cup was placed slightly deep to it. Postoperative radiograph analysis demonstrated a mean cup version of 20.8° and inclination of 44.7° using this method, and there had been no dislocations within a 12-month follow-up period.

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The TAL and PAW cannot be relied upon as intra-operative anatomical markers for acetabular cup orientation in cases of hip dysplasia [107].

Mechanical Alignment Guides (MAG's)

MAG's have been shown to significantly improve acetabular cup positioning and reduce errors in comparison to freehand techniques [102, 103]. One study investigated the correlation between the desired surgeon acetabular component positioning (anteversion and inclination) intra-operatively with the use of an MAG and the post-operative radiographic measurements in a series of 50 consecutive THR's [109]. The results suggested that acetabular component inclination can be reasonably assessed and reproduced intra-operatively with the use of an MAG, however anteversion cannot.

Digital Inclinometers (DI's)

A recent study by O'Neill *et al* investigated the accuracy of a 35° MAG's, DI's and freehand techniques in achieving a target operative inclination of 35° +/- 2.5° of the acetabular cup [94]. Uncemented cups, a posterior surgical approach, and a lateral decubitus position were used in all 270 patients within this study (90 in each group). The mean deviation from the target inclination was 1.8° in the MAG group, 1.3° in the DI group, and 2.9° in the freehand group. Statistically significant differences in the mean deviation from the target inclination were observed between the freehand/DI groups, freehand/MAG groups, and the DI/MAG groups. The DI allowed surgeons to achieve their target inclination in 88% of cases, compared to 71% in the MAG group, and 51% in the freehand group. These results would suggest that DI's are the most useful adjuncts for surgeons to reliably achieve a target acetabular inclination, followed by use of MAG's. DI's have also been incorporated into pelvic orientation devices (POD), which may be used to accurately determine the patients position on table in both the sagittal and transverse planes [110].



Figure 57: Commercially available Digital Inclinometer (DI) (Left), and Mechanical Alignment Guide (MAG) – Stryker® Trident™ (Right)

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Leg length (LL)

Leg length discrepancy (LLD) following THR is a common cause of patient dissatisfaction, poorer functional outcomes, limping, back pain, instability, and is a common reason for surgeon litigation [111-116]. LLD following THR may also be an indication for revision surgery if patients suffer significant pain or functional impairment as a direct result of it [115]. Considerable effort must therefore be made to achieve balanced and equal leg lengths for the patient. Surgeons are more likely to inadvertently increase a patient's leg length during a THR than shorten it [6, 117].

Post-operative LLD is most commonly due to mal-positioning of the femoral component, rather than the acetabular component [5, 111]. Perceived LLD following THR is common, with one study finding that 30% of patients reported a LLD between 5-8 years following a primary unilateral THR [111]. Although these patients reported a significantly lower Oxford Hip Score (OHS) than subjects who did not experience a functional LLD, a subsequent radiographic analysis revealed that only 36% of these patients had an anatomical LLD.

Minor LLD, usually defined as <10mm, are generally well tolerated by patients, and any discomfort settles over the first few post-operative months [113, 115, 117, 118]. A study using calibrated blocks on healthy subjects (n=30) reported that no participants reported discomfort with a 5mm LLD, whereas almost 97% noticed an artificially induced LLD of >10mm [119]. The authors recommendation was made to keep LLD to <10mm when performing a primary THR in order to prevent patient discomfort and awareness of LLD.

LLD can be described as either be functional or anatomical. Functional LLD is assessed clinically, and anatomical LLD is usually assessed radiographically. Functional LLD may be assessed by measuring the distance between either the patients ASIS and medial malleolus (true leg length), or a fixed point on the torso (commonly the umbilicus or xiphisternum) to the medial malleolus (apparent leg length). Another method is to use blocks of known thickness and placing them under the foot of the patient's shorter leg until the pelvis is balanced. These methods are susceptible to flexion contractures of the hip and/or knee, and pelvic obliquity caused for example by spinal pathology. The Galeazzi (aka Allis) test is used to assess which segment of a patient's leg (femur or tibia) is driving any apparent LLD[120]. This is most commonly used clinically in a paediatric patient population in for the assessment of developmental dysplasia of the hip (DDH), but may also be used in any suspected case of LLD. The test is performed with the patient supine with their pelvis square to the examination table, their hips flexed to 45°, knees flexed to 90°, and their feet flat on the examination table with their medial malleoli placed next to each other. The clinician looks for symmetry at the level of the knees. An inequality in the height or length of the knees is a positive Galeazzi sign. The knee shifts cephalad when the femoral length is reduced, and inferiorly when tibial length is reduced (see figure 58) [121].

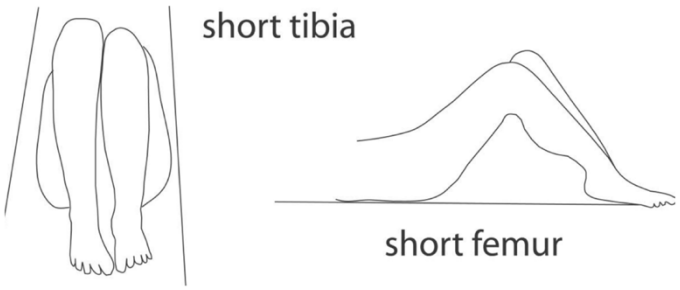


Figure 58: Galeazzi (Allis) test [121]

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Clinical methods of assessing LLD is known to have poor inter-and intra-rater reliability, and are not recommended for pre-operative leg length measurement [7]. If LLD is suspected, then formal leg length and alignment radiographs are recommended pre-operatively. These can be performed using either digitally amalgamated conventional radiographs of the full length of a patient's lower limbs (pelvis, femur, knees, tibia/fibula), or more commonly a CT scanogram. This will allow an accurate anatomical measurement of both leg lengths (femur/tibia), and assessment of both the mechanical and anatomical weight-bearing axis of the patient's lower limbs.

As emphasised in week 1 of this course, the role of pre-operative templating and planning in accurately reconstructing leg length cannot be overemphasised. Accurate templating will provide the surgeon with a clear plan of: the estimated pre-operative LLD; the level of the femoral neck osteotomy (which is critical in determining leg length in uncemented or collared femoral components; and the size and optimal positioning of both the acetabular and femoral components. If there are significant deviations in the size of the components intra-operatively, then this should alert the surgeon to the possibility of mal-positioning.

The type of anaesthetic may also influence the surgeon's ability to estimate and reconstruct leg length intra-operatively. One study demonstrated that LLD occurred significantly more often, with the operated leg being lengthened, in patients undergoing THR under RA compared to those under GA [122].

A variety of intra-operative techniques and tests have been described to help minimise the risk of post-operative LLD following THR. All of these require meticulous and secure patient positioning pre-operatively in order to assess the leg length intra-operatively.

Intra-operative positioning for leg length assessment

- The ASIS's should be positioned perpendicular to floor.
- The surgeon should maintain access to palpate both knees (tibial tuberosities), ankles (medial malleoli), and feet.
- A small pillow may be placed in between the patient's legs taking care not to block access to the above anatomical landmarks. This will help reduce adduction of superior (operative leg), which may falsely give the impression of leg shortening.
- A sandbag may be placed at the end of the table distal to the foot of the patients inferior (non-operative) leg in order to prevent this from moving during the operation.
- The surgeon should position the patient pre-operatively and check the leg lengths themselves on table both before and after skin preparation and draping.

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Intra-operative techniques for restoring LLD

The direct methods of intra-operative leg length assessment require the measurement of distance between two fixed anatomical landmarks on either the pelvis and/or femur [23].

1) Distance from the lesser trochanter to the neck osteotomy or femoral head COR.

This is more important for uncemented or collared femoral components. The majority of uncemented femoral stems come with a mechanical guide to assist in planning the level of the femoral neck osteotomy intra-operatively. In general, leaving a longer femoral neck results in an increased risk of lengthening the operative leg. A study by Gonzalez Della Valle *et al* used 3 measured distances to template the intra-operative position of a cemented femoral stem: 1) from the proximal corner of the lesser trochanter to the neck cut; 2) from the proximal corner of the lesser trochanter to the newly established femoral COR; and 3) the width of the calcar, medial to the stem at the level of the neck cut (see figure 59) [14]. The use of this technique during primary THR resulted in limb lengths within 5 mm of the contralateral side in 87.3% of patients.

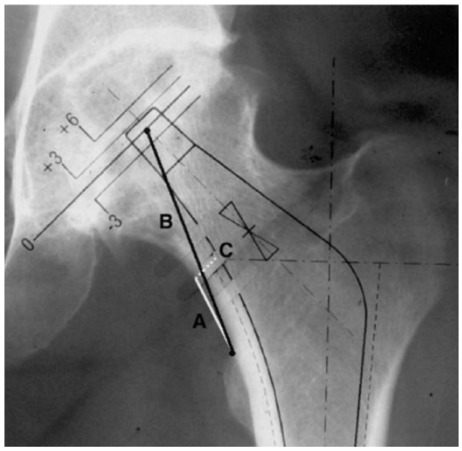


Figure 59: Templated distances from the proximal end of the lesser trochanter [14]

A: Distance from the proximal corner of the lesser trochanter to the neck cut

B: Distance from the proximal corner of the lesser trochanter to the femoral COR

C: The width of the calcar, medial to the stem at the level of the neck cut

A study by Lim *et al* used the femoral head to lesser trochanter distance (HLD) measured on PACS software for pre-operatively templating the position of the femoral component and assessed its impact on post-operative LLD following primary uncemented THR [123]. A ruler was used intra-operatively to measure the distance between the centre of the trial head and the superior edge of the lesser trochanter, and the surgeon selected the modular head that gave the distance nearest to the planned HLD. The use of this technique during primary THR resulted in limb lengths within 6 mm of the contralateral side in 81% of patients.

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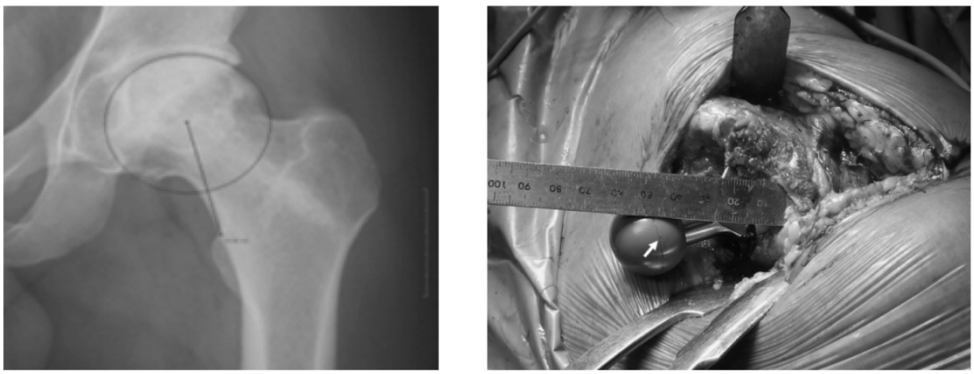


Figure 60: The femoral head to lesser trochanter distance (HLD) as used by Lim *et al* [123]

2) Distance from the tip of the greater trochanter to the shoulder of the femoral rasp or stem

The 'Exeter technique' was first described by Wilson, and validated by the Exeter group in in 2014 [42, 43]. This technique involves pre-operative templating of the ideal size, FO, and positioning of a cemented femoral stem in order to recreate the femoral COR. The optimum depth of the stem insertion is calculated by measuring the distance from the shoulder of the stem to the tip of the GT (see figure 61). This distance can be measured intra-operatively when trialling and/or implanting the femoral stem. Intra-operatively, the tip of the GT is identified by running a probe upwards along the endosteal surface of the lateral aspect of the femoral canal until it drops off superiorly. This point is then marked on the overlying soft tissue using a sterile marker pen or diathermy tip. The bony tip of the GT is not directly palpable superiorly as it is covered with the gluteus medius tendon insertion. Routine femoral preparation is then performed and a trial conducted to ensure satisfactory soft tissue tension, and leg lengths. A point on the broach handle/stem introducer may then be marked using a sterile pen at the same level at the tip of the GT, and also a small mark made of the femoral calcar corresponding with the laser marks/circular holes on the stem and broach respectively (see figure 61). Routine femoral cementing is then performed and the stem is inserted to the pre-determined depth. The use of this technique during primary THR resulted in limb lengths within <4 mm of the contralateral side in 96% of patients, with a mean post-operative LLD of 1.3 mm [43].

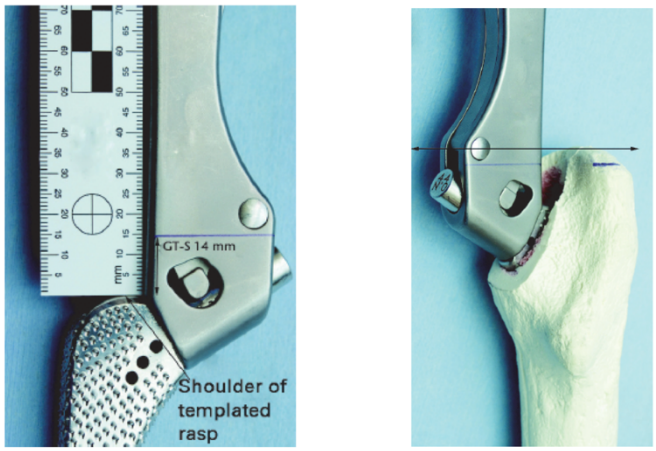


Figure 61: The Exeter technique of cemented stem insertion depth to recreate leg lengths

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3) Calliper or trans-osseous pin measurement

The use of callipers and trans-osseous pins to measure and help restore leg length and femoral offset in THR has been reported in a number of studies [24, 77, 112, 124-129]. The use of a calliper is thought to be quick, inexpensive, simple to use and can be applied to any design of femoral component [77]. However, access and training in the use of such callipers and intra-operative measurement techniques is currently not widespread in clinical practise. The techniques for trans-osseous pin placement involve placing a proximal Steinmann pin placed in a fixed peri-acetabular position, and another distally pin placed or mark made in the proximal femur. This allows the horizontal and vertical distance between them to be measured at the start and end of the operation [112]. The horizontal distance measured by either method represents the femoral offset, and the vertical distance represents the leg length. These methods are prone to significant error based upon minor changes in the position of the leg on table [23]. Another drawback to using single fixed points on the pelvis and femur to reference leg lengths and offsets from is that this 'combined' measurement fails to account for the individual contributions on the pelvic and femoral sides towards the total leg length and offset [77]. This point was raised Hill *et al* in a study which investigated the accuracy of a calliper designed to determine the stand alone femoral length and offset without any reference to the pelvis or acetabulum [77]. They argue that the anatomical restoration of length and offset for the femur and acetabulum should be addressed separately using patient-specific morphology (PSM) [77, 104, 130].

Intra-operative tests for assessing leg lengths

1) Leg to leg comparison at the knees

This is the most commonly used indirect test for leg length assessment in THR. The technique is as follows:

- Position both feet and medial malleoli together with the knees flexed to 90º and the hips flexed to 45º.
- The surgeon's open hand should be placed with the fingers flat against the tibial tuberosity of the patients inferior (non-operative) leg and held perpendicular to the operating table.
- The surgeon's other hand (usually left hand for a left THR) may then be used to measure the distance between their contralateral palm to the tibial tuberosity on the superior (operative) leg. This is usually measured in fingers breadth; however, a ruler may be used.
- This distance should be noted either mentally or written on the theatre board. If the patient has no LLD pre-operatively then the same distance needs to be achieved at the end of the operation. If the patients operative leg requires lengthening or shortening, then the amount should be factored into the distance of the leg length assessment.

The legs should always be positioned reproducibly when assessing leg lengths during the operation, i.e. the same degree of flexion/extension, ab/adduction, and internal/external rotation.

- Small changes in ab/adduction intra-operatively can cause substantial errors in measurement of the apparent leg length. One laboratory-based study demonstrated that 5° of femoral ab/adduction mal-positioning with the femur in neutral, flexed & extended positions causes 7.3-8.4mm of apparent leg length discrepancy, with 10° ab/adduction mal-positioning causing approximately 13.4 – 17.4mm leg length discrepancy [23].

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2) Drop Kick Test

The drop-kick test an indirect method of leg length, which assesses tension in the rectus femoris muscle. Any increase in the femoral length will lead to stretching and dysfunction of this muscle, resulting in a positive drop-kick test. The test is performed with the patient secured on table in the lateral decubitus position. The hip is held in extension, the knee is flexed to 90° and if the leg has not been lengthened the knee should remain flexed. If the knee extends this indicates tightness of the rectus femoris muscle, and infers that the femur has been excessively lengthened.

3) The Shuck test

This test was first described by Charnley. It is another indirect method of leg length assessment and soft-tissue tension in a reduced THR. It is usually performed during trialling, so that any modifications in leg length, femoral offset, or neck/head length may be made prior to the definitive component implantation. It is performed by the surgeon abducting and internally rotating the operative leg approximately 20º with one hand, and with the other hand placing two fingers (normally the index and middle), or a swab around the neck of the femoral stem and administering in-line lower limb traction in a distal direction. This should distract the prosthetic femoral head from acetabular cup. In a well tensioned THR trial there should be only few mm of shuck, and the THR should not be easily dislocated. If the femoral head is unable to be distracted from the acetabulum, this suggests that the leg is too long. A prospective RCT assessing 3 intra-operative methods to determine leg length (shuck test, trans-osseous pins and calliper, and leg-to-leg comparison at the knee) found that although all methods were positively correlated, the shuck test correlated best with the postoperative radiographic LLD among the 3 techniques [126]. However, one study has highlighted that the angle and force of traction administered by a surgeon performing a shuck test is not standardised, and this should be considered in the interpretation and reliability of this test [131].

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Surgical closure following THR

Secure closure of hip capsule and surrounding soft tissue envelope is known to reduce the incidence of post-operative dislocation [63]. Prior to wound closure it is important to lavage the hip joint thoroughly, and ensure that no 3rd body material, for example cement, is left within the hip joint. If using, local anaesthetic may be infiltrated around the hip capsule, surrounding musculature, and wound prior to closure.

Posterior approach

The hip capsule and piriformis tendon are the most critical structures to repair following a primary THR using the posterior approach. A systematic review reported that the posterior approach without soft tissue repair was found to have an 8.21 times greater relative risk of dislocation than with soft tissue repair [63]. This repair is facilitated by the previous 'tagging' of these structures using heavy sutures (e.g. 1 vicryl) during the surgical approach. The ends of these sutures may either be passed through trans-osseous drill holes and tied off on the lateral aspect of the greater trochanter, or by passing the needle directly through the outer cortex of the greater trochanter if the bone quality allows. The remainder of the SER's may then be repaired along their path using a continuous heavy suture. It is always important to note the position of the sciatic nerve whilst performing wound closure, as it is imperative not to transfix or incarcerate it within the soft tissues or suture material. The gluteus maximus and fascia lata may then be closed using a continuous heavy vicryl or loop PDS suture, prior to the fat layer and skin.

Direct lateral (Hardinge) approach

In addition to repairing the capsule using the heavy sutures with which it was tagged during the approach, the most important aspect when using this approach is to make a solid and meticulous repair of the vastus/gluteal muscle flap. This reduces the risk of persistent post-operative abductor weakness and a resultant Trendelenberg gait. Firstly, if the gluteus minimus tendon was identified and tagged during the approach then the heavy sutures may be used to secure this back down to the remaining soft tissue around its insertion on the anterior border of the greater trochanter. Passing the needle of the heavy suture directly through the outer cortex of the greater trochanter is also recommended if the bone quality allows. Repair of the vastus/gluteal muscle flap begins centrally with an interrupted heavy vicryl suture, usually with a double pass through the tissue to ensure a decent hold. This is tied off with a long end, which is left proud and then continued proximally along the flap in a continuous fashion before being tied off and cut at the proximal aspect of the gluteus medius incision. A second heavy vicryl suture is then started and tied off at the distal most aspect of the vastus lateralis split and passed in a continuous fashion towards the central aspect of the muscle flap. This is then tied off with the long end of the previous suture in order to complete the repair. Variations on the closure technique have been described, including the use of multiple interrupted 1 vicryl sutures followed by a running 1 vicryl suture to close the layer. The fascia lata, fat, and skin are then closed in a similar fashion to that described in the posterior approach.

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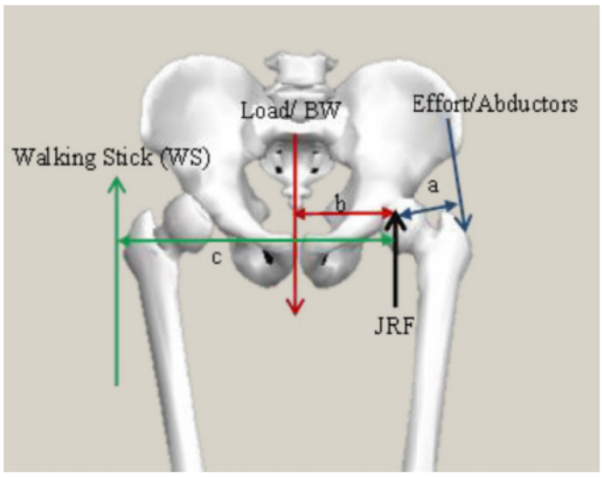
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Appendices

Hip Free Body Diagrams

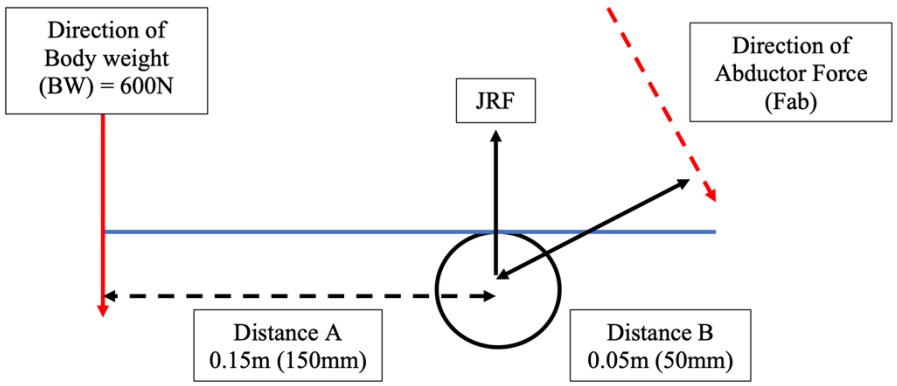
Free body diagrams are static 2-dimensional representations of joints that may be used to calculate the forces across a joint, such as the hip [81]. Free-body analysis makes several assumptions:

1) Bones are completely rigid and do not bend under load
2) Bone and muscles do not absorb any force
3) Forces only act in one plane
4) Joints are frictionless



Example of a free-body diagram of the pelvis and hip joints [81]

BW = Body weight **JRF = Joint reaction force**



Free-body diagram of the left hip joint

In order to resolve the above free-body diagram and calculate Fab, follow the steps below:

Fab x B = A x 5/6 BW

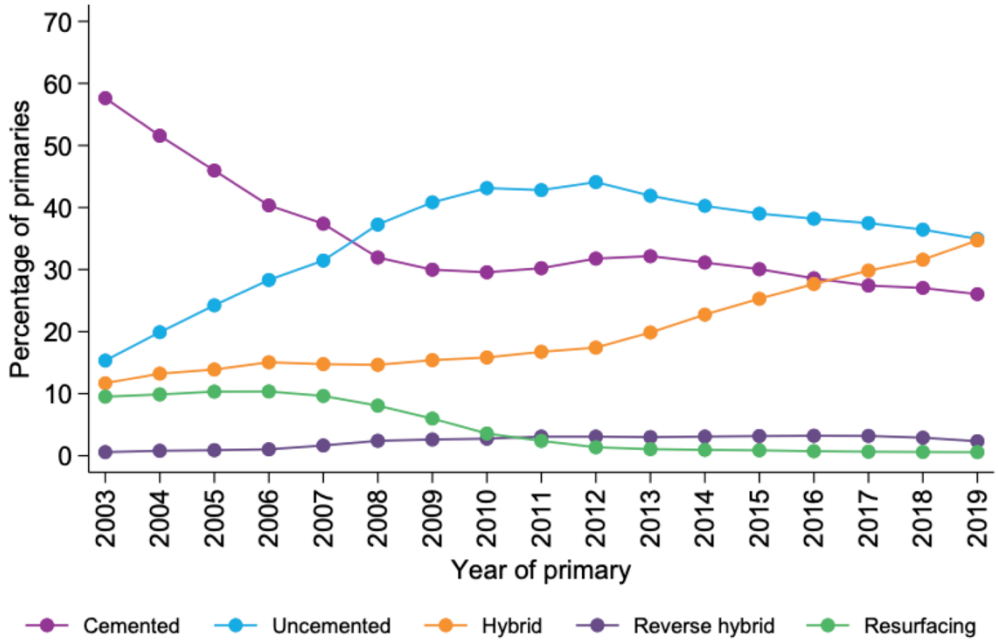
Fab x 0.05m = 0.15m x 500N

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Muscle	Origin	Insertion	Nerve supply	Blood supply	Action
Gluteal Muscles					
Gluteus Maximus	Posterior gluteal line of the ilium and iliac crest, dorsal surface of sacrum and coccyx and sacrotuberous ligament.	1) Superficial fibres insert onto the Ilio-tibial band of the fascia lata 2) Deeper fibres insert onto the gluteal tuberosity of the proximal femur between the vastus lateralis and adductor magnus	Inferior gluteal nerve (L5, S1, S2)	Superior gluteal artery supplies proximal 1/3 of muscle, and inferior gluteal artery supplies distal 2/3 of muscle	Hip extension and lateral rotation.
Gluteus Medius	Outer surface of the ilium between the iliac crest and posterior gluteal line above, and the anterior gluteal line below	Lateral surface of the greater trochanter	Superior gluteal nerve (L4, L5, S1)	Superior gluteal artery & veins	Hip extension, lateral rotation and abduction.
Gluteus Minimus	Outer surface of the ilium between the anterior and inferior gluteal lines	Anterior border of the greater trochanter	Superior gluteal nerve (L4, L5, S1)	Superior gluteal artery & veins	Abduction of the thigh particularly when the leg is extended.
Short External Rotators					
Piriformis	Anterior surface of the sacrum, gluteal surface of ilium, and sacro-tuberous ligament	Supero-medial border of the greater trochanter	Nerve to the piriformis (L5, S1, and S2)	Inferior gluteal, lateral sacral and superior gluteal artery	Externally (laterally) rotate the femur in the hip joint, and stabilize the hip joint.
Superior Gemellus	Ischial spine	Medial surface of the greater trochanter (trochanteric fossa)	nerve to obturator internus (L5, S1, S2)	Inferior gluteal artery & veins	
Obturator Internus	Anterior surface of the obturator membrane and ischio-pubic rami	Medial surface of the greater trochanter (trochanteric fossa)	Nerve to obturator internus (L5, S1, S2)	Inferior gluteal artery & veins	
Inferior Gemellus	Ischial tuberosity	Medial surface of the greater trochanter (trochanteric fossa) onto the obturator internus tendon	Nerve to quadratus femoris (L4-S1)	Inferior gluteal artery & veins	
Obturator Externus	Posterior medial surface of the obturator membrane and ischio-pubic rami	Medial surface of the greater trochanter (trochanteric fossa)	Posterior branch of obturator nerve	Obturator artery	
Quadratus Femoris	Lateral border of the ischial tuberosity	Quadrate tubercle on the intertrochanteric crest of the femur	Nerve to quadratus femoris (L4-S1)	Medial circumflex femoral artery	

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National Joint Registry (fixation and implant selection)



Temporal trends in THR component fixation [8]

Currently, the 3 most commonly used prostheses for acetabular cups and femoral stems are as follows:

Acetabular cup

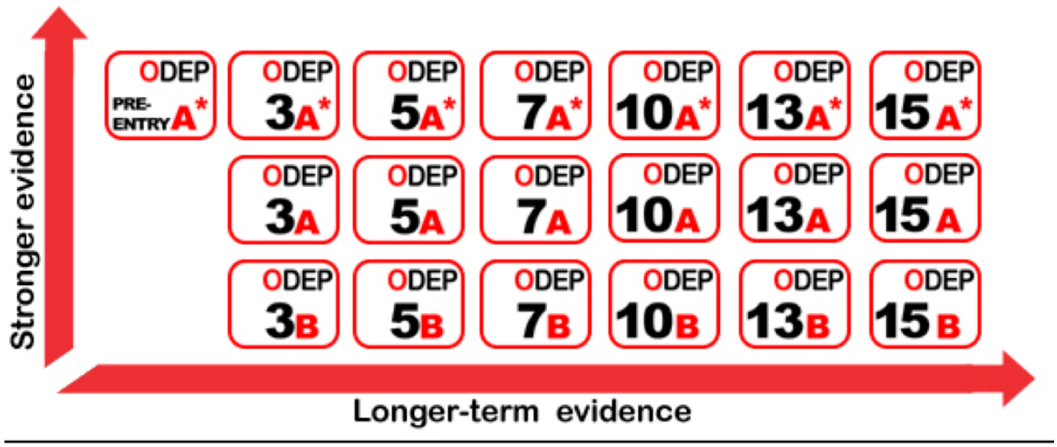
Cemented				Uncemented		
Manufacturer	**Brand**	**# and %**		**Manufacturer**	**Brand**	**# and %**
Stryker	Exeter Contemporary Flanged	n= 7,461 25%		DePuy	Pinnacle	n = 18,807 28%
DePuy	Marathon	n = 6,372 22%		Stryker	Trident	n = 16,310 25%
Stryker	Exeter X3 Rimfit	n = 4,937 17%		Smith & Nephew	R3 Cementless	n = 4,210 6%

Femoral stem

Cemented				Uncemented		
Manufacturer	**Brand**	**# and %**		**Manufacturer**	**Brand**	**# and %**
Stryker	Exeter V40	n = 33,709 60%		DePuy	Corail	n = 19.854 50%
Zimmer Biomet	CPT	n = 9,266 16%		Stryker	Accolade II	n = 2,588 7%
DePuy	C-stem AMT Cemented Stem	n = 5,233 9%		Smith & Nephew	Polarstem Cementless	n = 2,363 6%

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Orthopaedic Data Evaluation Panel (ODEP) Ratings



Bone Cement

Acrylic bone cement is polymethylmethacrylate (PMMA), a synthetic polymer of methylmethacrylate (MMA). PMMA was discovered in the early 1930's by British chemists, Rowland Hill and John Crawford, and was first used in THR by John Charnley in the 1950's [132, 133]. Charnley recognised that PMMA acted as a 'grout', not as glue, so that fixation was achieved by interlocking and not by adhesion. In THR, PMMA is used to 'fix' femoral stems or acetabular components into position.

PMMA is synthesised through a process of free-radical addition polymerisation after combining a liquid monomer with a powder polymer. This is an exothermic reaction, and can produce temperatures of approximately 82-86ºC *in-vivo* [134, 135]. This heat is dissipated through local blood flow and the prosthesis, however a cement mantle of <5mm is recommended to prevent osteonecrosis. The addition of heat-resistant antibiotics enables delivery of a high concentration of antibiotics locally around a prosthesis, thereby reducing the incidence of prosthetic joint infection (PJI), and a radio-opacifier allows the cement mantle to be visible on radiographs. PMMA is biologically inert, has a Young's Modulus similar to cancellous bone, a low elongation at breakage, and is one of the hardest thermoplastics with high scratch resistance [134]. PMMA is strongest in compression (90 MPa), in comparison to shear (45 MPa), or tensile forces (35 MPa).



Chemical structures of MMA and PMMA [134]

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The contents of the liquid and powder are outlined in the table below:

Liquid	Powder
Monomer: Methylmethacrylate (MMA)	**Polymer**: Polymethylmethacrylate (PMMA) co-polymer
Accelerator: N,N-dimethyl para-toludine	**Radio-opacifier:** Barium sulphate (BaSO4) or Zirconium Dioxide (ZrO2)
Inhibitor/stabiliser: Hydroquinone	**Polymerization initiator:** Benzoyl Peroxide (BPO)
	Antibiotics: Commonly Gentamycin, Clindamycin, or Vancomycin

Chlorophyll (green) or artificial pigment is sometimes added to aid visualisation of the cement.

PMMA is normally hand mixed in a vacuum sealed container at room temperature (23ºC / 73ºF). Vacuum mixing reduces evaporation of the liquid monomer and the porosity of PMMA. High viscosity cements are sometimes pre-chilled for use with mixing systems for easier mixing and prolonged working phase [135]. Following mixing, PMMA may be applied through a hand-pumped syringe or digitally.

The process of PMMA polymerisation, also known as the curing or setting process, progresses through several phases. High, medium, and low-viscosity bone cements are commercially available, and their individual progression throughout the phases differs. Viscosity affects the bone cement's handling characteristics, handling time, and its penetration into the cancellous bone and therefore, the quality and longevity of the fixation achieved [136]. In general, low-viscosity bone cements have a longer mixing phase and shorter working phase, with high viscosity cements having shorting mixing phases and longer working phase. Knowledge of the phases of the bone cement that you work with is important for any orthopaedic surgeon (see table below).

Phase	PMMA properties	Time
Phase 1 **The mixing phase**	Time to fully integrate the powder and liquid. Cement has a grainy sand-like liquid appearance. Low viscosity.	Up to 1 minute
Phase 2: **The sticky/waiting phase**	Cement has a smooth, consistent shiny appearance and sticks to gloves when handled.	Between 1-3 minutes
Phase 3: **The working phase**	Marked by the onset of cement 'scrotalisation', when the surface of the cement develops a slightly matt surface, wrinkles on light touch, and no longer sticks to the surgeon's gloves. Increased viscosity. **The prosthesis must be implanted before the end of the working phase**	Between 3-8 minutes
Phase 4: **The hardening or setting phase**	Cement hardens and sets. No movability. Peak temperature.	Between 8-11 minutes

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A number of clinically relevant environmental and chemical factors are known to affect the PMMA polymerisation process and quality of PMMA. The key variables, and their effects are summarised in the table below:

Temperature/Humidity	Increasing the temperature or humidity increases the rate of polymerisation, and reduces cement setting times. Increasing the temperature by 1° decreases the working and setting phases by approximately 5%.
Vacuum mixing	Mixing the liquid and powder in a vacuum decrease's porosity, and increases the strength of PMMA. Vacuum mixing decreases setting times.
Antibiotics/Antifungals	Addition of additional antibiotics and antifungals usually slows the polymerisation process, and increases cement setting times.
Manual handling	Handling of PMMA decreases setting times.

Cementing techniques in Orthopaedic surgery have evolved over time. A number modifications which have been proven to increase the quality of the cement mantle, and reduce complications have now been widely adopted when using bone cement. These are known as the 'generations' of cementing technique, and the key points for each generation are summarised in the table below:

Generation	Modification to cementing technique
1st	Hand mixing of cement in bowls. Minimal preparation of the femoral canal. Digital packing of cement into femoral canal.
2nd	Introduction of distal cement restrictor. Pulsed lavage of femoral canal Packing and drying of the femoral canal Suction catheter Retrograde insertion of cement using a gun.
3rd	Vacuum mixing of cement. Pressurisation of cement mantle
4th	Proximal and distal femoral stem centralisers

The clinical use of bone cement, particularly in relation to THR, is a known risk factor for peri-operative patient morbidity & mortality [137]. The most serious risk is bone cement implantation syndrome (BCIS), which in THR may occur during femoral instrumentation (preparation), cement insertion and pressurisation into the femoral canal or acetabulum, insertion of the prosthesis, or hip reduction. Although there is no consensus on the definition of BCIS, it is characterised by clinical features such as:

- Hypoxia
- Hypotension
- Cardiac dysrhythmia
- Increased pulmonary vascular resistance (PVR)
- Myocardial infarction

A number of patient factors have been associated with an increased risk of developing BCIS [137], namely:

- Older age and poor physiological reserve
- Impaired cardio-pulmonary function
- Pre-existing pulmonary hypertension
- Osteoporosis

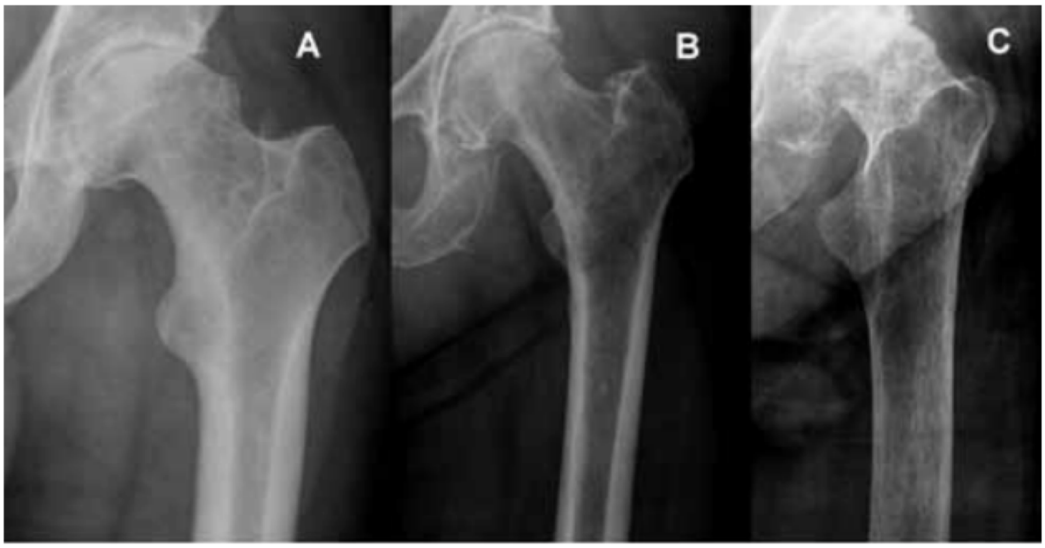
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- Hip fracture (particularly pathological or intertrochanteric)
- Bony metastases

The risk of a patient developing BCIS may be reduced by both surgeons and anaesthetists by [137]:

- Thorough and frequent lavage and suction of the femoral canal after each instrumentation.
- Surgical haemostasis
- Minimising the length of prosthesis
- Maintaining systolic BP above the pressure created on pressurising the femoral canal
- Increasing the inspired oxygen concentration at the time of cementing
- Avoiding intra-vascular volume depletion
- Consider invasive haemodynamic monitoring (central venous pressure and/or arterial line), and titrate vasopressors to maintain systolic BP at time of cementing.

Femoral morphology: The Dorr Classification



Examples of Dorr Type A, B, and C proximal femoral morphology [45]

Types A, B, and C have been described, which reflect a range of cortical thickness [44].

Type A bone is found more frequently in men than in women and more often in younger and heavier patients. Patients with type A proximal femurs have thicker cortices and less porosity, with a lower CC ratio and higher cortical indices. Type A bone has radiologically a good structural funnel shape and narrow lateral diaphyseal canal isthmus.

Type B bone is also more prevalent in men than in women. Patients with type B morphology have thinner cortices than Type A bone. The funnel shape of the canal remains good so that implant fixation is not a problem.

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Type C bone is found predominantly in women of older ages and lower body weight. It has both structural and cellular compromise. Cortices are thin with complete loss of the medial and posterior cortices resulting in a “stovepipe” shape of the intramedullary canal.

Particular note should be made of patients with Dorr type A proximal femoral morphology, as they exhibit thick cortices that begin at the distal end of the lesser trochanter and thicken quickly, producing a funnel shape and a narrow diaphyseal canal. This morphology may limit the passage of a standard femoral stem, especially when accounting for an adequate cement mantle.

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B.2 Pre- and Post-course Multiple Choice Questionnaires

Pre-course MCQ

Question 1

What is the polymerisation initiator in bone cement?

a) N,N-dimethyl para-toludine
b) Hydroquinone
c) Methylmethacrylate (MMA)
d) Barium sulphate (BaSO4)
e) Benzoyl Peroxide (BPO)

Question 2

Which spinal nerve roots form the sciatic nerve?

a) L3- S1
b) L3 – S2
c) L4 – S1
d) L4 – S2
e) L4 – S3

Question 3

Which of the following factors DOES NOT increase the lever arm of the hip joint?

a) Increasing the femoral offset
b) Varus angulation of the femoral stem
c) Valgus angulation of the femoral stem
d) Trochanteric osteotomy with distalisation and lateralisation
e) Increasing the combined offset (femoral and acetabular)

Question 4

When performing a cemented femoral stem, which Dorr type femur may concern you regarding the distal fit of the prosthesis?

a) Type A
b) Type B
c) Type C
d) Type D
e) Type E

Question 5

What is the recommended minimum and maximum bone cement mantle thickness to be used for fixing cemented THR components?

a) 1mm and <3mm
b) 1mm and <4mm
c) 2mm and <5mm
d) 2mm and <6mm
e) 2mm and >6mm

Question 6

What position should the lower limbs be placed in for optimal pre-operative assessment of the femoral offset?

a) 5-10º externally rotated
b) Neutral rotation
c) 5-9º internally rotated
d) 10-15º internally rotated
e) 16-20º internally rotated

Question 7

Pre-operative planning for THR is known to help with all except which of the following?

a) Ensuring that the appropriate size and type of implants and other special surgical equipment (for example bone graft, or augments) are requested in advance and available for use on the day of surgery.

b) Accurately recreate the patient's normal hip anatomy & biomechanics.

c) Anticipate and prepare for any variations in the operation.

d) Reduces the risk of iatrogenic sciatic nerve injury.

e) Collectively enhance the efficiency of the theatre team throughout the operation and the theatre list.

Question 8

What is the standard magnification for pelvic radiographs used in templating?

a) 90%
b) 100%
c) 110%
d) 120%
e) 130%

Question 9

Oversized acetabular cups are associated with which of the following complications?

a) Increased incidence of post-operative dislocation
b) Anterior overhang and iliopsoas impingement
c) Increased incidence of leg length discrepancy
d) Iatrogenic sciatic nerve injury
e) Mal-positioning of the cup

Question 14

What is considered to be a normal femoral neck-shaft angle?

a) <125º
b) 115 - 126º
c) 126 - 139º
d) 140-150º
e) > 150º

Question 15

Which is the thickest and strongest ligament forming the hip capsule?

a) Pubo-femoral ligament
b) The sacro-tuberous ligament
c) The Ilio-femoral ligament (of Bigelow)
d) The sacro-spinous ligament
e) Ischio-femoral ligament

Question 16

What radiographic line should the medial aspect of the acetabular cup NOT be placed medial to?

a) The obturator ring
b) The acetabular teardrop
c) Shenton's line
d) The iliopectineal line
e) The ilioischial line (Köhlers line)

Question 17

The femoral neck version is assessed off which anatomical landmark?

a) The femoral shaft in the sagittal plane
b) The femoral shaft in the coronal plane
c) The femoral shaft in the axial plane
d) The inter-trochanteric line
e) The posterior bicondylar line of the distal femur in the axial plane

Question 18

What is Lewineks 'safe zone'?

a) Radiographic anteversion (RA) of 10 +/- 10º and radiographic inclination (RI) of 45 +/- 10º
b) Radiographic anteversion (RA) of 15 +/- 10º and radiographic inclination (RI) of 40 +/- 10º
c) Operative anteversion (OA) of 10 +/- 10º and radiographic inclination (RI) of 45 +/- 10º
d) Operative anteversion (OA) of 15 +/- 10º and radiographic inclination (RI) of 40 +/- 10º
e) Anatomical anteversion (OA) of 15 +/- 10º and radiographic inclination (RI) of 40 +/- 10º

Question 10

According to Murray, how is operative anteversion defined?

a) The angle subtended between the transverse axis of the patient and the acetabular axis in the sagittal plane
b) The angle subtended between the transverse axis of the patient and the acetabular axis in the coronal plane
c) The angle subtended between the longitudinal axis of the patient and the acetabular axis in the sagittal plane.
d) The angle subtended between the longitudinal axis of the patient and the acetabular axis in the axial plane
e) The angle subtended between the longitudinal axis of the patient and the acetabular axis in the coronal plane

Question 11

What nerve is at risk with extension of the deep dissection beyond 5cm proximal to the greater trochanter when using the direct lateral (Hardinge) surgical approach?

a) Lateral Femoral Cutaneous nerve
b) Inferior Gluteal nerve
c) Sciatic Nerve
d) Superior Gluteal Nerve
e) Obturator Nerve

Question 12

The posterior approach to the hip joint exploits which inter-nervous plane?

a) Femoral and superior gluteal
b) Superior and inferior gluteal
c) Sciatic and superior gluteal
d) Sciatic and inferior gluteal
e) There is no true inter-nervous plane in the posterior approach to the hip

Question 13

Femoral offset (FO) is defined as…

a) The perpendicular distance between the centre of the femoral head and a line drawn down the shaft of the femur.
b) The distance from the centre of the femoral head to prominence of the lesser trochanter
c) The distance from the centre of the femoral head to the tip of the greater trochanter
d) The perpendicular distance from the medial border of the femoral head and a line drawn down the shaft of the femur.
e) The perpendicular distance from the acetabular teardrop and a line drawn down the shaft of the femur.

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b) 115 - 126º
c) 126 - 139º
d) 140-150º
e) > 150º

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c) Operative anteversion (OA) of 10 +/- 10º and radiographic inclination (RI) of 45 +/- 10º
d) Operative anteversion (OA) of 15 +/- 10º and radiographic inclination (RI) of 40 +/- 10º
e) Anatomical anteversion (OA) of 15 +/- 10º and radiographic inclination (RI) of 40 +/- 10º

Question 19

Which anatomical or radiographic marker may be used as a guide for the level of placement of the lower edge of the acetabular cup lie in the sagittal plane (supero-inferiorly)?

a) The transverse acetabular ligament (TAL)
b) The obturator foramen
c) Shenton's line
d) The acetabular (cotyloid) fossa
e) The iliopectineal line

Question 20

What is the pelvic 'safe-zone' for acetabular screw placement as described by Wasielewski?

a) Antero-inferior
b) Antero-superior
c) Postero-inferior
d) Postero-superior
e) Anterior or posterior

Post-course MCQ

Question 1

Regarding the implants used in THR, what does the number and letter in the Orthopaedic Data Evaluation Panel (ODEP) rating relate to?

a) The number represents the years since the product has been used in clinical practise, and the letter represents the infection rate of the product (A = low failure rate; B = moderate failure rate; C = high failure rate)

b) The number represents the current usage of the product in the UK market, and the letter represents the strength of evidence (A = strong evidence, B = acceptable evidence).

c) The number represents the number of years for which the products performance has been evidenced, and the letter represents the strength of evidence (A = strong evidence, B = acceptable evidence).

d) The number represents the number of years for which the products performance has been evidenced, and the letter represents the revision rate (A = low revision rate, B = high revision rate).

e) The number represents the number of years for which the products performance has been evidenced, and the letter represents the strength of evidence (A = strong evidence; B = acceptable evidence; C = limited evidence; D = No evidence)

Question 2

Which of the following factors increases the working & setting times of bone cement?

a) Increasing temperature
b) Increasing humidity
c) Vacuum mixing
d) Manual handling of cement
e) Decreasing temperature

Question 3

What is the anatomical reference plane for assessing femoral neck version?

a) The sagittal axis of the femur
b) The coronal axis of the femur
c) The posterior femoral condylar axis
d) The inter-trochanteric axis
e) The vertical plane of the tibia

Question 4

The calcium hydroxyapatite coating of uncemented femoral and acetabular prostheses is best described as what:

a) A ceramic compound with osteoconductive properties
b) A ceramic compound with osteogenic properties
c) A naturally occurring biological metallic alloy
d) A inert polymer which acts like grout
e) A bio-reactive polymer which acts like glue

Question 5

Which anatomical or radiographic marker may be used as a guide for the level of placement of the lower edge of the acetabular cup lie in the sagittal plane (supero-inferiorly)?

a) The iliopectineal line
b) The obturator foramen
c) Shenton's line
d) The acetabular (cotyloid) fossa
e) The transverse acetabular ligament (TAL)

Question 6

In patients with coxa valga, which of the following strategies would not typically be considered when attempting to recreate hip biomechanics?

a) Using an extended offset prosthesis
b) Leaving the femoral stem slightly proud if using a cemented stem
c) Performing a high femoral neck osteotomy if using an uncemented stem
d) Templating the native femoral centre of rotation
e) Recreating native femoral anteversion

Question 7

What is the effect on leg length and hip offset when using a +4mm extended head/neck on a femoral stem with a 125° neck-shaft angle (e.g. the Stryker Exeter or Corin Taperfit stems) ?

a) Increases length and offset by 4mm
b) Increases length by 4mm and offset remains the same
c) Increases offset by 4mm and the length remains the same
d) Increases length by approximately 2.3mm, and offset by 3.3mm
e) Increases offset by approximately 2.3mm and length by 3.3mm

Question 8

When pre-operatively templating and estimating femoral offset (FO), studies have shown that on average the use of plain radiographs:

a) Underestimates the FO by a mean value of 3.2mm
b) Underestimates the FO by a mean value of 6.4mm
c) Are equivalent to CT measurement
d) Overestimates the FO by a mean value of 3.2mm
e) Overestimates the FO by a mean value of 6.4mm

Question 9

An adequate radiograph of the pelvis, which is required for accurate pre-operative templating, should meet of all of the following criteria except:

a) The AP radiograph should be centred over the mid-point between the anterior-superior iliac spine (ASIS) and the pubic symphysis.

b) A marker ball of known size should be placed entirely within the radiograph, ideally between the patient's thighs and at the level of the greater trochanter.

c) The entirety of the pelvis must be visible, including both iliac crests, hip joints, and the proximal third of the femurs (to below the level of the lesser trochanters). The sacroiliac joints, pubic and ischial rami should also be visible.

d) The pelvis should appear symmetrical, with the coccyx being in line with the pubic symphysis, with the tip being located approximately 3cm above it.

e) Both femurs should be externally rotated by 15-20°.

Question 10

Placement of the anterior-superior retractor medial to the iliopsoas muscle and tendon risks injuring which structure?

a) Femoral nerve and vessels
b) Sciatic nerve
c) Obturator nerve
d) Superior gluteal nerve
e) Inferior glueal nerve

Question 11

Which vessel/s are most at risk when performing acetabular drill holes in the posterior-inferior quadrant of the pelvis close to the sciatic notch?

a) The external iliac artery
b) The external iliac vein
c) The superior & inferior gluteal vessels
d) The obturator vessels
e) The pudendal vessels

Question 12

An imaginary line through which two anatomical landmarks forms the dividing line between the anterior and posterior halves of the pelvic 'safe-zone' as described by Wasieleski?

a) The posterior-superior iliac spine and the pubic tubercle
b) The anterior and posterior superior iliac spines
c) The anterior superior iliac spine and the pubic tubercle
d) The anterior superior iliac spine and the centre of the cotyloid fossa
e) The anterior superior iliac spine and the ischial tuberosity

Question 13

What is the normal order of the short external rotators (SER's) from superior to inferior?

a) Superior Gemellus; Inferior Gemellus; Piriformis; Obturator Internus; Obturator Externus; Quadratus Femoris

b) Piriformis; Obturator Internus; Obturator Externus; Superior Gemellus; Inferior Gemellus; Quadratus Femoris

c) Piriformis; Superior Gemellus; Obturator Internus; Inferior Gemellus; Obturator Externus; Quadratus Femoris

d) Piriformis; Superior Gemellus; Inferior Gemellus; Obturator Internus; Obturator Externus; Quadratus Femoris

e) Obturator Internus; Piriformis; Obturator Externus; Superior Gemellus; Inferior Gemellus; Quadratus Femoris

Question 14

What is the most common course (~85% cases) of the sciatic nerve (SN) as it exits the pelvis?

a) The SN exits through the greater sciatic foramen as a single trunk, and passes ventrally beneath the piriformis muscle, and then dorsal to the remaining short external rotators.

b) The SN exits through the lesser sciatic foramen as a single trunk, and passes ventrally beneath the piriformis muscle, and ventrally to the remaining short external rotators.

c) The SN divides into it peroneal and tibial division within the pelvis and then exits through the lesser sciatic foramen as a single trunk, and passes ventrally beneath the piriformis muscle, and ventrally to the remaining short external rotators.

d) The SN divides into it peroneal (CPN) and tibial (TN) division within the pelvis and then exits through the greater sciatic foramen, with the CPN piercing the piriformis muscle, and the TN passing below and ventrally to the piriformis muscle.

e) The SN exits through the greater sciatic foramen as a single trunk, and passes dorsal to the piriformis muscle and the remaining short external rotators.

Question 15

What does the Drop Kick test assess?

a) Femoral offset
b) Stability of the THR
c) Rectus femoris tension
d) Range of Movement
e) Short external rotator tension

Question 16

The results of *in-vitro* study by Grammatopoulos *et al* into acetabular component positioning using models of a posterior approach to the hip suggest that surgeons tend to:

a) Underestimate operative anteversion (OA) and underestimate operative inclination (OI)

b) Overestimate operative anteversion (OA) and underestimate operative inclination (OI)

c) Overestimate operative anteversion (OA) and overestimate operative inclination (OI)

d) Underestimate operative anteversion (OA) and overestimate operative inclination (OI)

e) Achieve both operative anteversion (OA) and operative inclination (OI)

Question 17

What is the relationship between acetabular Operative inclination (OI) and Radiographic Inclination (RI)?

a) OI is generally 5º greater than RI
b) OI is generally 5º less than RI
c) OI is generally equal to RI
d) OI is generally 10º greater than RI
e) OI is generally 10º less than RI

Question 18

According to the results of a study in 2018 by O'Neill *et al* what is the average degree of on table pelvic adduction (sag)?

a) 1°
b) 3°
c) 5°
d) 7°
e) 9°

Question 19

97% of healthy subjects notice an artificially induced (using wooden blocks) leg length discrepancy of:

a) <4mm
b) 4-6mm
c) 6-8mm
d) 8-10mm
e) >10mm

Question 20

Increasing the femoral offset during a THR has all of the following effects except:

a) Creates a larger abductor moment arm
b) Increases the risk of dislocation
c) Decreases the hips joint-reaction force
d) Increases the stability of the THR
e) Increases the range of movement of a THR

C. General Appendix for Study Chapter 6

C.1 Protocol for Patriot and MetaMotion R sensor set-up, motion data recording & analysis

Patriot set-up and data recording

- Sequence of turning on PiMGR programme and sensors:
  - Patriot sensor link box off
  - Turn Patriot sensor link box on – green light should appear front right
  - Turn on PiMGR programme
- Position Patriot sensors
  - Mid-point of the dorsum of the 3rd metacarpal
  - 3cm distal to lateral epicondyle of distal humerus in line with shaft of radius

- **Device > Tracker configuration**
  1. cm – apply
- **Device > Station configuration**
  1. Select both sensors
  2. + X
- Output Data (order specific)
  1. Time stamp
  2. Frame count
  3. Position
  4. Euler Angles
  5. ASCII/CLIF

Apply – ok.

Press C to start data collection on sensors.

Press Toggle to record data (ctrl + R) and stop at end (F12).

Select file > export motion recording > file type .txt

Save to folder with manos.m and process_patriot_data_for_manos2.m scripts

RESET the Patriot System before each experiment

Patriot data processing

Open MatLab

Set directory to folder with:

1. .txt data file
2. manos.m script
3. process_patriot_data_for_manos2.m script

Open process_patriot_data_for_manos2.m script and run using .txt file from Patriot system

This should produce a MANOS.txt file, which is saved into the same folder

Open manos.m script and run using MANOS.txt file

In the MatLab Command Window this should produce

1. Path travelled
2. Movement counts

Metamotion R sensors set-up

- Must have MBient Lab MetaBase API downloaded onto iOS, Android, or Windows device
- Update firmware
- Sensor data acquisition: Linear acceleration (100Hz)
- Data streaming or logging options available.
  - Data streaming more effective for longer data acquisition periods (>15minutes)
  - Data logging max 8MB and takes time to download following experiment

- Position MMR sensors
  - Mid-point of the dorsum of the 3rd metacarpal
  - 3cm distal to lateral epicondyle of distal humerus in line with shaft of radius

- Select sensor – new session – select data acquisition parameters as described above – press start –
- Screen stating SUCCESS The sensors have been configured and started logging data will appear, alongside a red dot on the right side of the chosen sensor on the home screen
- To stop recording select sensor -press download – name session
- Forward downloaded data using e-mail or airdrop if sensor in logging mode.

All data must be saved in .csv format

IMU sensor data processing using MatLab

Pre-requisites for processing

- Scripts (process.m, and process_elimNaNs) and .csv files must be contained within the same folder.

1) Open MatLab
2) Run process (try process.m initially)
3) Select.csv file (takes time to load)
    a. Separate files available for each side (LEFT/RIGHT)
4) Timing file should appear with attached counts
    a. Rename and save as LEFT/RIGHT

If timings file appears to have NaN (Not Applicable Number), then re-run above process using process_elimNaNs MatLab code

IMU sensor data processing using RStudio and Activity Counts

1. Open RStudio
2. Load Template for Activity Counts
3. Ensure all requisite packages are installed
4. Check that the letters specified in the timings file match timings (start/stop/duration) for letters in RCode
5. Click files (bottom right)
    a. Single click files for motion data
    b. Click import Dataset'
    c. Copy and paste file URL into brackets of LEFT/RIGHT/times read.csv code in Step1
6. Save file as R Script into folder containing motion data and timings
    a. File > save as
7. Remove any blocks of code for letters which are not relevant (e.g., 'H' for initial trial)

    a. ‘ADD TIMINGS HERE’ section
    b. ‘STEP Movement Counts’ section
    c. ‘Print results’ section
8. Highlight and Run Code for sections 1-5, stopping at ‘ADD TIMINGS HERE’
9. This should print a tibble of start/stop timings to enter manually into ‘ADD TIMINGS HERE’ section
10. Double check timings match name in ‘ADD TIMINGS HERE’ section
11. Highlight and Run Code for ‘ADD TIMINGS HERE’ section
12. Remove NA’s (unmatched data from LEFT/RIGHT hands) from COMBINEDcount by selecting and running code for Step 6.
13. Check number of rows in COMBINEDcount and ensure that final step in ‘ADD TIMINGS HERE’ section does not exceed this number. If this does, then:
    a. Make final number in the last defined step in ‘ADD TIMINGS HERE’ section match the total number of rows in COMBINEDcount dataframe.
    b. Select and re-run code for this step
14. Select and run code for both summary and step movement count sections
15. Select and run code for print results section.

D. General Appendix for Study Chapter 7

D.1 Central University Research Ethics Approval (CUREC) for Study

MEDICAL SCIENCES INTERDIVISIONAL RESEARCH ETHICS COMMITTEE
Research Services, University of Oxford, Wellington Square, Oxford, OX1 2JD
Tel: +44(0)1865 616577 Fax: +44(0)1865 280467
ethics@medsci.ox.ac.uk



CONFIDENTIAL Ref: R57808/RE001

Mr Daniel Howgate
Nuffield Department of Orthopaedics, Rheumatology
& Musculoskeletal Sciences (NDORMS)
University of Oxford
Old Road
OX3 7LD

9th July 2019

Dear Daniel,

Research Ethics Approval - CUREC 1

Study title: Simulation-based orthopaedic surgery training programme

Short title: Oxford OrthoSim

The above application has been considered on behalf of the Medical Sciences Interdivisional Research Ethics Committee (IDREC) in accordance with the procedures laid down by the University for Ethical Approval of all research involving human participants.

I am pleased to inform you that, on the basis of the information provided to the IDREC, the proposed research has been judged as meeting appropriate ethical standards, and approval has been granted for a period of **5 years**, commencing on **5th August 2019**. The reference number for this study is **R57808/RE001**.

This is **subject to:**

a) **it is your responsibility to comply with the requirements for administering any tests or questionnaires and, if in doubt, to contact the publisher of those tests or questionnaires.**

b) **if new research staff are engaged, the PI is responsible for ensuring they are suitably qualified by training and/or experience.**

I would like to remind you that your study may be selected for review by the MS IDREC during an annual audit.

Amendments

Should there be any subsequent changes to the study, you should submit details to the MS IDREC for consideration and approval. Details of changes must be listed on an amendment form. If your study received University Sponsorship through CTRG, then the amendment will first need to be submitted to CTRG for approval of continued Sponsorship.

Please do not hesitate to contact me if you have any queries.

Yours Sincerely

H. Barnby-Porritt

Dr. Helen Barnby-Porritt
Research Ethics Manager, Medical Sciences

D.2 Participant Information Sheet and Informed Consent Forms

Nuffield Department of Orthopaedics, Rheumatology &
Musculoskeletal Sciences,
University of Oxford,
Old Road,
OX3 7LD

Participant Information Sheet

Simulation-based orthopaedic surgery training programme

(MSD-IDREC R57808/RE001)

This sheet describes the purpose of the study, and explains what is involved. Please read the information below carefully before deciding whether or not you would like to take part.

What is the purpose of the study?

Total Hip Replacement (THR) is one of the most commonly performed, cost-effective, and successful Orthopaedic operations. Over 90,000 THR are performed within the National Health Service (NHS) of the United Kingdom every year. The primary aim of this research study is to assess and objectively determine the effectiveness and impact of simulation training on the performance of Surgical Trainees and Medical Students during simulated components of a Total Hip Replacement (THR) operation. Consultant Surgeons and Arthroplasty Fellows will also be included in the assessments as comparator groups, but will not be eligible to undertake additional simulation training.

Gaining 'clinical competence' in surgery is a complex and multifactorial process that takes years of experience and training. However, modern surgical training has to adapt to the constraints of modern surgical practice, which includes:

- The constant evolution of surgical techniques and technology.
- Increasing demand for surgery, twinned with increasing complexity of cases.
- Increased patient expectations, and Consultant-led care.
- Restriction in working hours.
- Increased pressure for theatre efficiency, and service provision from hospital management.

We strongly believe that simulation training has a significant role to play in addressing some of these deficiencies by enhancing surgical training, operative experience, and the competence of surgical trainees in a safe environment. This study is part of a wider research programme investigating the role of simulation training both in Orthopaedics and the wider surgical field, which will take place over a five-year period within the Oxford Orthopaedic Simulation & Education Centre (OOSEC).

Why have I been chosen?

We are recruiting participants with a wide range of experience from Medical Students through to Consultant Surgeons.

The broad spectrum of participants included within this study will hopefully allow us to objectively determine the performance for each level of training, and therefore allow us to effectively map out the typical surgical learning curve of participants as they progress through their surgical training.

Where will the study take place?

This study will take place within the Oxford Orthopaedic Simulation and Education Centre (OOSEC).

The OOSEC is a secure self-contained laboratory space within the Nuffield Department of Orthopaedics, Rheumatology & Musculoskeletal Sciences (NDORMs) area on the 1st floor of the Nuffield Orthopaedic Centre (NOC).

Nuffield Department of Orthopaedics, Rheumatology &
Musculoskeletal Sciences,
University of Oxford,
Old Road,
OX3 7LD

Do I have to take part?

No. It is entirely up to you to decide whether or not to take part. If you agree, we will ask you to sign a consent form to confirm your decision to participate. ***Even after you have signed this consent form and agreed to join the study, you may withdraw from the study without penalty at any time without giving a reason.*** A decision not to take part or to withdraw at any time will not affect you in any way.

What do I have to do if I take part?

The involvement of each individual participant within this study will be determined by their position at the point of enrolment, which, in turn, will dictate the group they are placed in. The two groups are as follows:

1) ***The Intervention group***, consisting of:
Medical Students, Foundation Trainee's, Core Surgical Trainee's, and Higher Surgical Trainee's.

   Participants within the Intervention group will be randomised (50:50) to receive one of the following:

   1) Regular Deanery/Medical School Teaching & Training.
   2) Additional simulation-based training for approximately 1 hour per week over 4 weeks.

2) ***The Comparator group***, consisting of:
Arthroplasty Fellows and **Consultant Orthopaedic Surgeons.**

Tasks and timetable

All participants will be required to make an initial visit to the OOSEC to confirm eligibility, complete a consent form indicating that you agree to take part in this study, and have an introductory tour of the facilities. Following this, the details of your specific group dependent tasks and timetable will be issued. The outline of which is as follows:

1) The Intervention Group

Regular training ('control') sub-group

- Baseline written & practical skills assessment within the OOSEC within 3 months following enrolment. This will last approximately 1 hour.
- Final written & practical skills assessment within the OOSEC to be undertaken at approximately 3 months following the baseline assessment. This will last approximately 1 hour.

Simulation training ('intervention') sub-group

- Baseline written & practical skills assessment within the OOSEC within 3 months following enrolment. This will last approximately 1 hour
- Weekly simulation training sessions within the OOSEC for 4 consecutive weeks, with each session lasting approximately 1-2 hours
  - Week 1: Set-up & surgical approach to a THR
  - Week 2: Acetabular preparation & implantation
  - Week 3: Femoral preparation & implantation
  - Week 4: Reconstructing hip anatomy and summary session
- Final written & practical skills assessment within the OOSEC to be undertaken at approximately 3 months following the baseline assessment. This will last approximately 1 hour.

2) The Comparator Group

- Baseline practical skills assessment within the OOSEC within 3 months following enrolment. This will last approximately 1 hour

Nuffield Department of Orthopaedics, Rheumatology &
Musculoskeletal Sciences,
University of Oxford,
Old Road,
OX3 7LD

At the start of each session one of the researchers will outline the tasks and the simulator to be used in more detail, and answer any questions that you have. You will then be shown an introductory video. We may ask you to fill in a short one-page feedback questionnaire after using the simulator. Following completion of this study, and upon request, all participants randomised into the regular training group will have the opportunity to undertake the additional simulation-based training programme.

What are the possible benefits to taking part?

Your participation in the study will allow us to answer the research questions underlying this study, and to explore the effects of simulation on simulated surgical performance in one of the most commonly performed and successful orthopaedic operations. You will have the opportunity of experiencing and helping to develop new assessment methods which may be used in the future evaluation of competence in orthopaedic surgery. You will have the opportunity to practice, develop, and objectively determine your surgical skills under supervision in the simulation laboratory, which may in turn highlight areas for personal development and improvement.

What are the possible disadvantages and risks of taking part?

Although your surgical skills performance is being evaluated, this is only for the purpose of this research study. Results from the assessments and feedback within this study WILL NOT form be reported to any regulatory bodies, or affect your career progression in any way. All data generated within this study will be anonymized, and you will not be identified in any analysis comparisons and publications that might arise. Following completion of this study, all participants will be informed of the results of their individual performances, which will be anonymously reported in comparison to the average group level results of participants of other training levels. It will be up to the professional judgement of the individual participant to reflect and act upon their results.

Participants will be expected to engage in low-risk simulated surgical activities within the OOSEC. Such activities may include the use of power tools, saws, or sharp instruments. As part of the baseline visit, the lead investigator, or suitably qualified and experienced deputy, will outline the materials and tasks involved in advance of each training session.

What if there is a problem?

If a participant in research is ever considered to have suffered harm through their participation, the University has arrangements in place to provide for compensation. If you have a concern about any aspect of this study, please speak to the lead researcher ***Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk], or their supervisor Professor Jonathan Rees [jonathan.rees@ndorms.ox.ac.uk]***, who will do their best to answer your query. The researcher should acknowledge your concern within 10 working days and give you an indication of how they intend to deal with it. If you remain unhappy or wish to make a formal complaint, please contact the Chair of the Medical Sciences Interdivisional Research Ethics Committee (MS IDREC) at the University of Oxford who will seek to resolve the matter in a reasonably expeditious manner: Email: ethics@medsci.ox.ac.uk; Address: Research Services, University of Oxford, Wellington Square, Oxford OX1 2JD.

Will my taking part in this study be kept confidential?

The information you provide as part of the study is the **research data**. Any research data from which you can be identified (e.g. your name, audio-visual recordings, or consent forms), is known as **personal data**. It does not include data where the identity has been removed (anonymous data). We will minimise our use of personal data in the study as much as possible.

Nuffield Department of Orthopaedics, Rheumatology &
Musculoskeletal Sciences,
University of Oxford,
Old Road,
OX3 7LD

All research and personal data will be securely stored on a password encrypted hard-drive, which will be kept in a locked cupboard on the study site for a minimum of 5 years after the end of the study period for the purpose of 'public interest task' before being destroyed.

The researcher and research team (supervisor or collaborators) will have access to the research data and anonymous data, but not your personal data. Responsible members of the University of Oxford and the relevant NHS Trust may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

We would like your permission to use fully anonymised direct quotes in research publications.

Data Protection

The University of Oxford is the data controller with respect to your personal data and, as such, will determine how your personal data is used in the study.

The University will process your personal data for the purpose of the research outlined above. Research is a task that we perform in the public interest.

Further information about your rights with respect to your personal data is available http://www.admin.ox.ac.uk/councilsec/compliance/gdpr/individualrights/.

What will happen to the results of the research study?

The results of the study will be analysed by the research team and presented at departmental meetings, conferences and published in clinical peer-reviewed journals. Some of the research being undertaken will also contribute to the fulfilment of an educational requirement (e.g. a doctoral thesis). No individual participant will be identified in any report or presentation arising from the research.

Who is organising the research?

This study will be run by a research team based at the Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences.

Who has reviewed the study?

The study has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee.

Further information and contact details

If you are unsure about taking part in this study then please take some time to consider the information and ask more questions. For more information, please contact:

Prof Jonathan Rees MBBS, FRCS (Eng), MD, FRCS (Tr&Orth)
Professor of Orthopaedic Surgery and Musculoskeletal Science,
Botnar Institute of Musculoskeletal Sciences,
University of Oxford, Old Road,
Oxford OX3 7LD.
Email: jonathan.rees@ndorms.ox.ac.uk
Tel: 01865 737540

Nuffield Department of Orthopaedics, Rheumatology,
and Musculoskeletal Sciences

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences,
University of Oxford,
Old Road, Oxford
OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

PARTICIPANT CONSENT FORM

Simulation-based orthopaedic surgery training programme

(MSD-IDREC R57808/RE001)

Purpose of Study: To determine the effectiveness and quantify the impact of simulation training on the performance of Surgical Trainees and Medical Students during simulated components of a total hip replacement operation.

		Please initial each box
1	I confirm that I have read and understand the information sheet version _____ dated _____ for the above study. I have had the opportunity to consider the information carefully, ask questions and have had these questions answered satisfactorily.	☐
2	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without any adverse consequences or academic penalty.	☐
3	I have been advised about the potential risks associated with taking part in this research and have taken these into consideration before consenting to participate.	☐
4	I have been advised as to what I need to do for this research and I agree to follow the instructions given to me.	☐
5	To the best of my knowledge, I do not meet any of the exclusion criteria outlined in the information sheet for this research. If this changes at a later date during study participation, I agree to notify the researchers immediately.	☐
6	I understand that data collected during the study may be looked at by designated individuals from the University of Oxford. I give permission for these individuals to access my data.	☐
7	I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	☐
8	I agree for data collected in this study to be shared with other researchers, including those working outside of the EU, to be used in other research studies. I understand that any data shared will be fully anonymised so that I cannot be identified.	☐

9	I understand how this research will be written up and published.	☐
10	I understand that this project has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee.	☐
11	I understand how to raise a concern or make a complaint.	☐
12	I agree to take part in the study	☐

_____	dd / mm / yyyy	_____
Name of Participant	Date	Signature

_____	dd / mm / yyyy	_____
Name of person taking consent	Date	Signature

E. General Appendix for Study Chapter 8

E.1 Clinical Trial and Research Governance Approval for Study

RESEARCH SERVICES
Clinical Trials and Research Governance
Joint Research Office
Boundary Brook House
Churchill Drive
Headington, Oxford
OXON
OX3 7GB

To whom it may concern

Date: 07/08/2019

Dear Sir/Madam,

Title: A prospective randomised controlled study assessing the impact of simulation training in primary total hip replacement (THR).

PID: 14471

Protocol Date/Version: 06.08.2019 Version 1.0

The above study has been designed by Prof Jonathan Rees and colleagues at the University of Oxford and funded by the Dinwoodie Charitable Company. I confirm that the University will accept the role of Research Sponsor of this Study and will comply with the requirements of the UK Policy Framework for Health and Social Care Research October 2017.

Insurance-provided indemnity arrangements are in place for the project:
Newline Underwriting Management Ltd., at Lloyd's of London.

Sponsorship is confirmed subject to the condition that the following are sent to Clinical Trials and Research Governance for review prior to submission to the Research Ethics Committee. Failure to do so may compromise insurance cover for the project.

- Any minor or substantial amendments
- Any extension to the study end date
- Addition of any new research site or patient identification centre

In addition, annual progress reports, the end of study notification and final report must be copied to Clinical Trials and Research Governance.

Lastly, where they exist, University Core SOPs must be followed by default for all clinical research sponsored by the University. Further information can be found here: https://researchsupport.admin.ox.ac.uk/ctrg/resources

Any communications relating to Research Sponsorship should be directed to the undersigned, whose contact details are given in this letter.

Yours faithfully

Nigel Wellman
Clinical Trials and Research Governance

Tel: +44 (0)1865 616480 Web: https://researchsupport.admin.ox.ac.uk/ctrg
Email: Heather.house@admin.ox.ac.uk or Elaine.Chick@admin.ox.ac.uk

E.2 Research Ethics Committee (REC) Approval for Study

NHS
Health Research Authority

South Central - Oxford B Research Ethics Committee
Whitefriars
Level 3, Block B
Lewin's Mead
Bristol
BS1 2NT
Telephone: 020 7104 8049

Please note: This is the favourable opinion of the REC only and does not allow you to start your study at NHS sites in England until you receive HRA Approval

22 October 2019

Professor Jonathan Rees
Botnar Research Centre
Old Road
Oxford
OX3 7LD

Dear Professor Rees

Study title:	**A prospective randomised controlled study assessing the impact of simulation training in primary total hip replacement (THR).**
REC reference:	**19/SC/0492**
Protocol number:	**0000000**
IRAS project ID:	**270167**

Thank you for your letter of 15th October 2019, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation subject to the conditions specified below.

Confirmation of Capacity and Capability (in England, Northern Ireland and Wales) or NHS management permission (in Scotland) should be sought from all NHS organisations involved in

the study in accordance with NHS research governance arrangements. Each NHS organisation must confirm through the signing of agreements and/or other documents that it has given permission for the research to proceed (except where explicitly specified otherwise).

Guidance on applying for HRA and HCRW Approval (England and Wales)/ NHS permission for research is available in the Integrated Research Application System.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of management permissions from host organisations

Registration of Clinical Trials

It is a condition of the REC favourable opinion that **all clinical trials are registered** on a publicly accessible database. For this purpose, 'clinical trials' are defined as the first four project categories in IRAS project filter question 2. Registration is a legal requirement for clinical trials of investigational medicinal products (CTIMPs), except for phase I trials in healthy volunteers (these must still register as a condition of the REC favourable opinion).

Registration should take place as early as possible and within six weeks of recruiting the first research participant at the latest. Failure to register is a breach of these approval conditions, unless a deferral has been agreed by or on behalf of the Research Ethics Committee (see here for more information on requesting a deferral: https://www.hra.nhs.uk/planning-and-improving-research/research-planning/research-registration-research-project-identifiers/

As set out in the UK Policy Framework, research sponsors are responsible for making information about research publicly available before it starts e.g. by registering the research project on a publicly accessible register. Further guidance on registration is available at: https://www.hra.nhs.uk/planning-and-improving-research/research-planning/transparency-responsibilities/

You should notify the REC of the registration details. We will audit these as part of the annual progress reporting process.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

After ethical review: Reporting requirements

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study, including early termination of the study

- Final report

The latest guidance on these topics can be found at https://www.hra.nhs.uk/approvals-amendments/managing-your-approval/.

Ethical review of research sites

NHS/HSC sites

The favourable opinion applies to all NHS/HSC sites listed in the application subject to confirmation of Capacity and Capability (in England, Northern Ireland and Wales) or management permission (in Scotland) being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS/HSC sites

I am pleased to confirm that the favourable opinion applies to any non-NHS/HSC sites listed in the application, subject to site management permission being obtained prior to the start of the study at the site.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Confirmation of any other Regulatory Approvals (e.g. CAG) and all correspondence [Central University Research Ethics Approval for Simulation Training]		09 July 2019
Copies of advertisement materials for research participants [Surgeon Participant recruitment e-mail]	1.0	06 August 2019
Evidence of Sponsor insurance or indemnity (non NHS Sponsors only) [University of Oxford Clinical Trials Insurance]		26 July 2019
IRAS Application Form [IRAS_Form_08082019]		08 August 2019
IRAS Checklist XML [Checklist_15102019]		15 October 2019
Letter from funder [Letter from funder]		30 April 2018
Letter from sponsor [University of Oxford CTRG sponsorship letter]		07 August 2019
Organisation Information Document [OID]	2.0	12 October 2019
Other [Response to reviewers following REC meeting 8.10.19]	2.0	12 October 2019
Participant consent form [Surgeon PCS]	2.0	12 October 2019
Participant consent form [Surgeon PCS]	2.0	12 October 2019
Participant consent form [Patient PCS]	2.0	12 October 2019
Participant information sheet (PIS) [Patient PIS]	2.0	12 October 2019
Participant information sheet (PIS) [Surgeon PIS]	2.0	12 October 2019
Participant information sheet (PIS) [Patient PIS]	2.0	12 October 2019
Research protocol or project proposal [Clinical Research Protocol]	1.0	06 August 2019
Summary CV for Chief Investigator (CI) [Summary CV for CI]		06 August 2019
Summary CV for student [Summary CV for student]		06 August 2019

Summary CV for supervisor (student research) [Summary CV for Supervisor]		06 August 2019
Summary, synopsis or diagram (flowchart) of protocol in non technical language [Study Flow Chart]		06 August 2019
Validated questionnaire [Oxford Hip Score]		06 August 2019
Validated questionnaire [EQ-5D]		06 August 2019

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

User Feedback

The Health Research Authority is continually striving to provide a high quality service to all applicants and sponsors. You are invited to give your view of the service you have received and the application procedure. If you wish to make your views known please use the feedback form available on the HRA website:
http://www.hra.nhs.uk/about-the-hra/governance/quality-assurance/

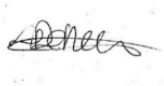
HRA Learning

We are pleased to welcome researchers and research staff to our HRA Learning Events and online learning opportunities– see details at:
https://www.hra.nhs.uk/planning-and-improving-research/learning/

19/SC/0492	**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project.

Yours sincerely
PP



Mr Chris Foy
Chair

Email:nrescommittee.southcentral-oxfordb@nhs.net

Enclosures: "After ethical review – guidance for researchers" *[SL-AR2]*

Copy to: N/A N/A CTRG

Summary CV for supervisor (student research) [Summary CV for Supervisor]		06 August 2019
Summary, synopsis or diagram (flowchart) of protocol in non technical language [Study Flow Chart]		06 August 2019
Validated questionnaire [Oxford Hip Score]		06 August 2019
Validated questionnaire [EQ-5D]		06 August 2019

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

User Feedback

The Health Research Authority is continually striving to provide a high quality service to all applicants and sponsors. You are invited to give your view of the service you have received and the application procedure. If you wish to make your views known please use the feedback form available on the HRA website:
http://www.hra.nhs.uk/about-the-hra/governance/quality-assurance/

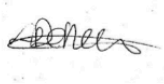
HRA Learning

We are pleased to welcome researchers and research staff to our HRA Learning Events and online learning opportunities– see details at:
https://www.hra.nhs.uk/planning-and-improving-research/learning/

19/SC/0492	**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project.

Yours sincerely
PP



Mr Chris Foy
Chair

Email:nrescommittee.southcentral-oxfordb@nhs.net

Enclosures: "After ethical review – guidance for researchers" *[SL-AR2]*

Copy to: N/A N/A CTRG

E.3 NHS Health Research Authority (HRA) Approval for Study

Ymchwil Iechyd a Gofal Cymru
Health and Care Research Wales

NHS
Health Research Authority

Professor Jonathan Rees
Botnar Research Centre
Old Road
Oxford
OX3 7LD

Email: hra.approval@nhs.net
HCRW.approvals@wales.nhs.uk

29 October 2019

Dear Professor Rees

HRA and Health and Care Research Wales (HCRW) Approval Letter

Study title:	**A prospective randomised controlled study assessing the impact of simulation training in primary total hip replacement (THR).**
IRAS project ID:	**270167**
Protocol number:	**0000000**
REC reference:	**19/SC/0492**
Sponsor	**University of Oxford/Clinical Trials and Research Governance**

I am pleased to confirm that **HRA and Health and Care Research Wales (HCRW) Approval** has been given for the above referenced study, on the basis described in the application form, protocol, supporting documentation and any clarifications received. You should not expect to receive anything further relating to this application.

Please now work with participating NHS organisations to confirm capacity and capability, in line with the instructions provided in the "Information to support study set up" section towards the end of this letter.

How should I work with participating NHS/HSC organisations in Northern Ireland and Scotland?
HRA and HCRW Approval does not apply to NHS/HSC organisations within Northern Ireland and Scotland.

If you indicated in your IRAS form that you do have participating organisations in either of these devolved administrations, the final document set and the study wide governance report (including this letter) have been sent to the coordinating centre of each participating nation. The relevant national coordinating function/s will contact you as appropriate.

Please see IRAS Help for information on working with NHS/HSC organisations in Northern Ireland and Scotland.

How should I work with participating non-NHS organisations?
HRA and HCRW Approval does not apply to non-NHS organisations. You should work with your non-NHS organisations to obtain local agreement in accordance with their procedures.

What are my notification responsibilities during the study?

The standard conditions document "*After Ethical Review – guidance for sponsors and investigators*", issued with your REC favourable opinion, gives detailed guidance on reporting expectations for studies, including:

- Registration of research
- Notifying amendments
- Notifying the end of the study

The HRA website also provides guidance on these topics, and is updated in the light of changes in reporting expectations or procedures.

Who should I contact for further information?
Please do not hesitate to contact me for assistance with this application. My contact details are below.

Your IRAS project ID is **270167**. Please quote this on all correspondence.

Yours sincerely,
Claudia Bywater
Approvals Specialist

Email: hra.approval@nhs.net

Copy to: *CTRG*

E.4 Consultant and Fellow Participant Information Sheet

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

SURGEON PARTICIPANT INFORMATION SHEET: CONSULTANTS & ARTHROPLASTY FELLOWS

A prospective randomised controlled study assessing surgical performance and the impact of simulation training in primary THR

We'd like to invite you to take part in our research study. Before you decide, it is important that you understand why the research is being done and what it would involve for you. Please take time to read this information, and discuss it with others if you wish. *If there is anything that is not clear, or if you would like more information, please ask us.*

What is the purpose of the study?

This research study is focused upon assessing and optimising surgical trainee's performance during, and patient outcomes following, total hip replacement (THR) surgery. The primary research question is to determine if additional simulation training can improve the intra-operative performance of surgical trainees (Specialty Registrars) during a THR, or the outcome of patients after their THR. We will also aim to define an 'expert' standard in performing a primary elective THR, which may be used as a benchmark when assessing surgical trainee performance; and also determine if operative surgeon performance metrics during a THR are correlated with surgical experience, or patient outcomes. This study forms part of a wider educational research project in part fulfilment of a Doctor of Philosophy Degree (DPhil or PhD) in Musculoskeletal Sciences for the lead researcher (DH).

Where will the study take place?

The two recruitment centres for this study are:

- The **Nuffield Orthopaedic Centre** (NOC), Oxford University Hospitals NHS Trust
- **Wycombe General Hospital** (WGH), Buckinghamshire Healthcare NHS Trust

Why have I been invited?

As a Consultant Orthopaedic Hip Surgeon or senior Arthroplasty Fellow you will be regularly performing THR operations, and represent the 'expert' level of operative performance and clinical competence. We would like to assess your intra-operative metrics in order to define this 'expert' standard of performance in primary THR, against which surgical trainees may be judged as part of their clinical training and competence assessment.

Do I have to take part?

No. It is entirely up to you to decide whether or not to take part. If you agree, we will ask you to sign a consent form to confirm your decision to participate. ***Even after you have signed this consent form***

and agreed to join the study, you may withdraw from the study without penalty at any time without giving a reason. A decision not to take part or to withdraw at any time will not affect you in any way.

What will happen to me if I decide to take part?

If you choose to enrol in this study, you will firstly be asked to sign a consent form to confirm your participation. Following this, we will invite you to attend the Oxford Orthopaedic Simulation & Education Centre (OOSEC) for a practical skills assessment. We will then assess your intra-operative performance using motion analysis from wireless elbow sensors on up to 5 separate primary THR operations.

Tasks and timetable

All participants will be required to make an initial visit to the OOSEC to confirm eligibility, complete a consent form indicating that you agree to take part in this study, and have an introductory tour of the facilities. Following this, we ask that you allow us to perform the following:

1) Baseline practical skills assessment within the OOSEC within 3 months following enrolment. This will last less than 1 hour

2) Intra-operative assessment using wireless elbow motion sensors on up to 5 separate primary elective THR.

Are there any possible disadvantages or risks from taking part?

Although your surgical skills performance is being evaluated, this is only for the purpose of this research study. Results from the assessments and feedback within this study WILL NOT form be reported to any regulatory bodies.

What are the possible benefits of taking part?

Your participation in the study will allow us to answer the research questions underlying this study, and to explore the impact of simulation training on surgical performance in THR. You will form the 'expert' comparator group, which will hopefully help to benchmark the optimum standard of performance in a primary elective THR. This has never been attempted before. Following completion of this study, all participants will be informed of the results of their individual performances, which will be anonymously reported in comparison to the average group level results of participants of other training levels. It will be up to the professional judgement of the individual participant to reflect and act upon their results.

Will my taking part in the study be kept confidential?

The information you provide as part of the study is the **research data**. Any research data from which you can be identified (e.g. your name, or consent forms), is known as **personal data**. It does not include data where the identity has been removed (anonymous data). We will minimise our use of personal data in the study as much as possible.

All research and personal data will be securely stored on a password encrypted hard-drive, which will be kept in a locked cupboard on the study site for of 5 years after the end of the study period for the purpose of 'public interest task' before being destroyed.

The researcher and research team (supervisor or collaborators) will have access to the research data and anonymous data, but not your personal data. Responsible members of the University of Oxford

and the relevant NHS Trust may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

We would like your permission to use fully anonymised direct quotes in research publications.

Will I be reimbursed for taking part?

There will be no financial reimbursement for taking part. The other benefits of taking part are outlined above.

What will happen to my data?

Data protection regulation requires that we state the legal basis for processing information about you. In the case of research, this is 'a task in the public interest.' The University of Oxford is the data controller and is responsible for looking after your information and using it properly.

We will be using information from your intra-operative surgical performance in order to undertake this study and will use the minimum personally-identifiable information possible. We will destroy any identifiable information about you after the study has finished. This excludes any research documents with personal information, such as consent forms, which will be held securely at the University of Oxford for 5 years after the end of the study. Data from this study could be made available in the event of a medico-legal situation.

Data protection regulation provides you with control over your personal data and how it is used. When you agree to your information being used in research, however, some of those rights may be limited in order for the research to be reliable and accurate. Further information about your rights with respect to your personal data is available at:
http://www.admin.ox.ac.uk/councilsec/compliance/gdpr/individualrights/

Responsible members of the University of Oxford may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

You can find out more about how we use your information by contacting the lead researcher **Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk].**

What will happen if I don't want to carry on with the study?

Your participation in this study is voluntary, and you are free to change your mind at a later stage. Withdrawal from this study will not affect you in any way. If you withdraw from the study, we will destroy all your identifiable data, but will use the anonymised data collected up to your withdrawal.

What will happen to the results of this study?

The results of the study will be analysed by the research team and presented at departmental meetings, conferences and published in clinical peer-reviewed journals. Some of the research being undertaken will also contribute to the fulfilment of an educational requirement (e.g. a doctoral thesis). No individual participant will be identified in any report, publication or presentation placed in the public domain from this research. Following completion of this study, all participants will be informed of the results of their individual performances, which will be anonymously reported in comparison to the average group level results of participants of other training levels. It will be up to the professional judgement of the individual participant to reflect and act upon their results.

What if there is a problem?

The University of Oxford, as Sponsor, has appropriate insurance in place in the unlikely event that you suffer any harm as a direct consequence of your participation in this study. NHS indemnity operates in respect of the clinical treatment which is provided. If you wish to complain about any aspect of the way in which you have been approached or treated, or how your information is handled during the course of this study, you should contact **Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk]**, or their supervisor **Professor Jonathan Rees [jonathan.rees@ndorms.ox.ac.uk]**, who will do their best to answer your query. The researcher should acknowledge your concern within 10 working days and give you an indication of how they intend to deal with it. You may also contact the **University of Oxford Clinical Trials and Research Governance (CTRG) office on 01865 616480, or the head of CTRG [ctrg@admin.ox.ac.uk]**.

Who is organising and funding the study?

This study will be run by a research team based at the Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences (NDORMs), with funding provided by the Dinwoodie Charitable Research Company, and approval from the Royal College of Surgeons (RCS) of England.

Who has reviewed the study?

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee, to protect participants' interests. This study has been reviewed and given favourable opinion by the Clinical Trials Research Ethics Committee.

Further information and contact details:

If you are unsure about taking part in this study, then please take some time to consider the information and ask more questions. For more information, please contact:

Prof Jonathan Rees MBBS, FRCS (Eng), MD, FRCS (Tr&Orth)
Professor of Orthopaedic Surgery and Musculoskeletal Science,
Botnar Institute of Musculoskeletal Sciences,
University of Oxford, Old Road,
Oxford OX3 7LD.
Email: jonathan.rees@ndorms.ox.ac.uk
Tel: 01865 737540

Thank you for considering taking part.

E.5 Specialty Registrar Participant Information Sheet

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

SURGEON PARTICIPANT INFORMATION SHEET: SPECIALTY REGISTRARS

A prospective randomised controlled study assessing surgical performance and the impact of simulation training in primary THR

We'd like to invite you to take part in our research study. Before you decide, it is important that you understand why the research is being done and what it would involve for you. Please take time to read this information, and discuss it with others if you wish. *If there is anything that is not clear, or if you would like more information, please ask us.*

What is the purpose of the study?

This research study is focused upon assessing and optimising surgical trainee's performance during, and patient outcomes following, total hip replacement (THR) surgery. The primary research question is to determine if additional simulation training can improve the intra-operative performance of surgical trainees (Specialty Registrars) during a THR, or the outcome of patients after their THR. We will also aim to define an 'expert' standard in performing a primary elective THR, which may be used as a benchmark when assessing surgical trainee performance; and also determine if operative surgeon performance metrics during a THR are correlated with surgical experience, or patient outcomes. This study forms part of a wider educational research project in part fulfilment of a Doctor of Philosophy Degree (DPhil or PhD) in Musculoskeletal Sciences for the lead researcher (DH).

Where will the study take place?

The two recruitment centres for this study are:

- The **Nuffield Orthopaedic Centre** (NOC), Oxford University Hospitals NHS Trust
- **Wycombe General Hospital** (WGH), Buckinghamshire Healthcare NHS Trust

Why have I been invited?

All **Specialty Registrars (StR's)** who hold a National Training Number in Trauma & Orthopaedic Surgery, and who will be undertaking clinical placements in Adult Hip Arthroplasty within the next 2 years are invited to participate in this study. This is because you will all be regularly performing THR operations under supervision as part of your clinical training. This will allow us the opportunity to assess your intra-operative performance, and also follow-up the patients who you operate on as primary surgeon.

Do I have to take part?

No. It is entirely up to you to decide whether or not to take part. If you agree, we will ask you to sign a consent form to confirm your decision to participate. ***Even after you have signed this consent form and agreed to join the study, you may withdraw from the study without penalty at any time without giving a reason.*** A decision not to take part or to withdraw at any time will not affect you in any way.

What will happen to me if I decide to take part?

If you choose to enrol in this study, you will firstly be asked to sign a consent form to confirm your participation. Following this, the StR group will be randomised in a 1:1 ratio to receive either:

1) Routine Deanery teaching & training **PLUS** Additional simulation training (the intervention group) This will be delivered in a supervised laboratory setting within the simulation lab at the Nuffield Orthopaedic Centre over a 4-week period. Each training session will be scheduled after the Regional Wednesday afternoon teaching, and will last approximately 1 hour.

2) Routine Deanery teaching & training (the control group).

Following completion of the above training (if applicable), we will follow you and all participants at 6-week intervals throughout your 6-month clinical placements in order to monitor your intra-operative performance when performing a THR as first surgeon under supervision on patients within the NHS.

Tasks and timetable

All participants will be required to make an initial visit to the Oxford Orthopaedic Simulation & Education Centre (OOSEC) to confirm eligibility, complete a consent form indicating that you agree to take part in this study, and have an introductory tour of the facilities. Following this, the details of your specific group dependent tasks and timetable will be issued. The outline of which is as follows:

The Intervention Group: Regular Deanery teaching & training PLUS additional simulation training

- Baseline written & practical skills assessment within the OOSEC within 3 months following enrolment. This will last approximately 1 hour.
- Weekly simulation training sessions within the OOSEC for 4 consecutive weeks, with each session lasting approximately 1 hour
  - **Week 1**: Set-up & surgical approach to a THR
  - **Week 2**: Acetabular preparation & implantation
  - **Week 3**: Femoral preparation & implantation
  - **Week 4**: Reconstructing hip anatomy and summary session
- Final written & practical skills assessment within the OOSEC to be undertaken at approximately 3 months following the baseline assessment. This will last approximately 1 hour.

***The Control Group*: Regular Deanery teaching & training**

- Baseline written & practical skills assessment within the OOSEC within 3 months following enrolment. This will last approximately 1 hour.
- Final written & practical skills assessment within the OOSEC to be undertaken at approximately 3 months following the baseline assessment. This will last approximately 1 hour.

At the start of each session one of the researchers will outline the tasks and the simulator to be used in more detail, and answer any questions that you have. You will then be shown an introductory video. We may ask you to fill in a short one-page feedback questionnaire after using the simulator.

Following completion of this study, and upon request, all participants randomised into the regular training group will have the opportunity to undertake the additional simulation-based training programme. We will also request summaries of you eLogbook, specifically looking at the number of THR performed.

Are there any possible disadvantages or risks from taking part?

Although your surgical skills performance is being evaluated, this is only for the purpose of this research study. Results from the assessments and feedback within this study WILL NOT be reported to any regulatory bodies, or affect your career progression in any way.

What are the possible benefits of taking part?

Your participation in the study will allow us to answer the research questions underlying this study, and to explore the impact of simulation training on surgical performance during, and patient outcomes following THR. You will have the opportunity of experiencing new competency assessment methods, and may also undertake additional novel simulation training allowing you to practice and possibly improve your surgical skills. Following completion of this study, all participants will be informed of the results of their individual performances, which will be anonymously reported in comparison to the average group level results of participants of other training levels. It will be up to the professional judgement of the individual participant to reflect and act upon their results.

Will my taking part in the study be kept confidential?

The information you provide as part of the study is the **research data**. Any research data from which you can be identified (e.g. your name, or consent forms), is known as **personal data**. It does not include data where the identity has been removed (anonymous data). We will minimise our use of personal data in the study as much as possible.

All research and personal data will be securely stored on a password encrypted hard-drive, which will be kept in a locked cupboard on the study site for of 5 years after the end of the study period for the purpose of 'public interest task' before being destroyed.

The researcher and research team (supervisor or collaborators) will have access to the research data and anonymous data, but not your personal data. Responsible members of the University of Oxford and the relevant NHS Trust may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

We would like your permission to use fully anonymised direct quotes in research publications.

Will I be reimbursed for taking part?

There will be no financial reimbursement for taking part. The other benefits of taking part are outlined above.

What will happen to my data?

Data protection regulation requires that we state the legal basis for processing information about you. In the case of research, this is 'a task in the public interest.' The University of Oxford is the data controller and is responsible for looking after your information and using it properly.

We will be using information from your intra-operative surgical performance in order to undertake this study and will use the minimum personally-identifiable information possible. We will destroy any identifiable information about you after the study has finished. This excludes any research documents

with personal information, such as consent forms, which will be held securely at the University of Oxford for 5 years after the end of the study. Data from this study could be made available in the event of a medico-legal situation.

Data protection regulation provides you with control over your personal data and how it is used. When you agree to your information being used in research, however, some of those rights may be limited in order for the research to be reliable and accurate. Further information about your rights with respect to your personal data is available at:

http://www.admin.ox.ac.uk/councilsec/compliance/gdpr/individualrights/

Responsible members of the University of Oxford may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

You can find out more about how we use your information by contacting the lead researcher **Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk].**

What will happen if I don't want to carry on with the study?

Your participation in this study is voluntary, and you are free to change your mind at a later stage. Withdrawal from this study will not affect you in any way. If you withdraw from the study, we will destroy all your identifiable data, but will use the anonymised data collected up to your withdrawal.

What will happen to the results of this study?

The results of the study will be analysed by the research team and presented at departmental meetings, conferences and published in clinical peer-reviewed journals. Some of the research being undertaken will also contribute to the fulfilment of an educational requirement (e.g. a doctoral thesis). No individual participant will be identified in any report, publication or presentation placed in the public domain from this research. Following completion of this study, all participants will be informed of the results of their individual performances, which will be anonymously reported in comparison to the average group level results of participants of other training levels. It will be up to the professional judgement of the individual participant to reflect and act upon their results.

What if there is a problem?

The University of Oxford, as Sponsor, has appropriate insurance in place in the unlikely event that you suffer any harm as a direct consequence of your participation in this study. NHS indemnity operates in respect of the clinical treatment which is provided. If you wish to complain about any aspect of the way in which you have been approached or treated, or how your information is handled during the course of this study, you should contact **Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk]**, or their supervisor **Professor Jonathan Rees [jonathan.rees@ndorms.ox.ac.uk]**, who will do their best to answer your query. The researcher should acknowledge your concern within 10 working days and give you an indication of how they intend to deal with it. You may also contact the **University of Oxford Clinical Trials and Research Governance (CTRG) office on 01865 616480, or the head of CTRG [ctrg@admin.ox.ac.uk]**.

Who is organising and funding the study?

This study will be run by a research team based at the Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences (NDORMs), with funding provided by the Dinwoodie Charitable Research Company, and approval from the Royal College of Surgeons (RCS) of England.

Who has reviewed the study?

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee, to protect participants' interests. This study has been reviewed and given favourable opinion by the Clinical Trials Research Ethics Committee.

Further information and contact details:

If you are unsure about taking part in this study, then please take some time to consider the information and ask more questions. For more information, please contact:

Prof Jonathan Rees MBBS, FRCS (Eng), MD, FRCS (Tr&Orth)
Professor of Orthopaedic Surgery and Musculoskeletal Science,
Botnar Institute of Musculoskeletal Sciences,
University of Oxford, Old Road,
Oxford OX3 7LD.
Email: jonathan.rees@ndorms.ox.ac.uk
Tel: 01865 737540

Thank you for considering taking part.

E.6 Patient Participant Information Sheet

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk.

PATIENT INFORMATION SHEET

THR PERFORMANCE & ASSESSMENT

We'd like to invite you to take part in our research study, which is focussed upon surgeon's performance during, and patient outcomes following, total hip replacement (THR) surgery.

The surgeon participants will all be members of your direct clinical care team, and will be divided into two groups based upon their experience and seniority. The 'expert' group will consist of consultants & senior fellows, and the 'trainee' group will consist of specialty registrars in trauma & orthopaedic surgery. Surgeons within the 'trainee' group will be randomly allocated to receive either standard training, or standard training with additional training on hip simulator models. We aim to assess the impact of this additional training on their performance during surgery. Consultant surgeons and senior fellows will not receive any additional training. During your surgery we will use special sensors to safely monitor the hand movements of all surgeon participants (experts and trainees), as a measure of performance. All surgeon participants will have the appropriate experience to perform the surgery, and all trainees will be directly supervised by senior clinicians.

Before you decide, it is important that you understand why the research is being done and what it would involve for you. Please take time to read this information, and discuss it with others if you wish.

If there is anything that is not clear, or if you would like more information, please ask us.

1. ***What is the purpose of the study?***

The purpose of this study is to see if extra training for junior surgeons (specialty registrars) on hip simulators can result in even better patient outcomes after total hip replacement (THR) surgery in the NHS. We hope that the results of this study will lead to further improvements in surgical training, performance, and even better patient outcomes following THR. This study forms part of a wider educational research project in part fulfilment of a Doctor of Philosophy Degree (DPhil or PhD) in Musculoskeletal Sciences for the lead researcher (DH).

2. ***Why have I been chosen?***

You are due to have a routine planned total hip replacement soon for painful osteoarthritis of your hip, and we will be assessing a group of up to 30 surgeons performing THR on patients such as yourself within the NHS at the two Hospitals named below.

3. ***Where will the study take place?***

The study is taking place in two Hospitals:

1) The Nuffield Orthopaedic Centre (NOC), Oxford University Hospitals NHS Trust.
2) Wycombe General Hospital (WGH), Buckinghamshire Healthcare NHS Trust.

4. ***Do I have to take part?***

No. It is entirely up to you to decide whether or not to take part. If you agree, we will ask you to sign a consent form to confirm your decision to participate. ***Even after you have signed this consent form and agreed to join the study, you may withdraw from the study without penalty at any time without giving a reason.*** A decision not to take part, or to withdraw at any time will not affect the care you receive.

5. ***What do I have to do if I take part?***

If you are eligible and choose to join the study, then we will ask for your written informed consent to participate when you attend your routine pre-operative assessment clinic (POAC) appointment with your Consultant Orthopaedic Surgeon. Following this we are asking two things of you:

1) To complete two simple short questionnaires (called the EQ-5D, and the Oxford Hip Score). These will need to be completed once before, and once again after your operation. They check your views on your current health, and how well you are doing after your hip replacement. The first pair of questionnaires will need to be completed before your operation in your POAC, and the second pair will need to be completed when you attend your routine post-operative out-patient clinic appointment at approximately 8 weeks following your operation.

2) We would also like to ask for your consent to access the routine information collected in your hospital medical records about your recovery after your hip replacement, such as your blood tests, your x-rays before and after your operation, and other details of your recovery or anything that slowed it down.

6. ***What are the possible disadvantages and risks of taking part?***

The actual risks of having a hip replacement will be explained to you by your Consultant as part of the surgical consent process. There are ***no additional risks*** involved for you personally by taking part in the study. You will receive exactly the same care that you would have received if you did not take part, under the same Consultant Surgeon and their respective team.

7. ***What are the possible benefits to taking part?***

Although you will not directly benefit by taking part in this study, your participation might allow us to answer the research questions outlined at the start of this information sheet. Namely, does extra surgeon training result in even better patient outcomes after total hip replacement (THR) surgery in the NHS? Our findings will hopefully lead to improvements in surgical training and possibly even better patient outcomes following THR.

8. ***Will my taking part in this study be kept confidential?***

Any information collected, or any comments or opinions expressed by you during the course of this study, will be ***strictly confidential***, and will not be attributable to you. If the study is published in a book or scientific journal, no individual patients will be identified in any way.

Responsible members of the University of Oxford may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.

9. ***What will happen to my data?***

Data protection regulation requires that we state the legal basis for processing information about you. In the case of research, this is 'a task in the public interest.' The University of Oxford is the data controller and is responsible for looking after your information and using it properly.

We will use the minimum personally-identifiable information possible. We will destroy any identifiable information about you after the study has finished. This excludes any research documents with personal information, such as consent forms, which will be held securely at the University of Oxford for 5 years after the end of the study. Data from this study could be made available in the event of a medico-legal situation.

Data protection regulation provides you with control over your personal data and how it is used. When you agree to your information being used in research, however, some of those rights may be limited in order for the research to be reliable and accurate. Further information about your rights with respect to your personal data is available at:

http://www.admin.ox.ac.uk/councilsec/compliance/gdpr/individualrights/

10. ***What will happen to the results of the research study?***

The results of the study will be analysed by the research team and presented at meetings, conferences and published in scientific peer-reviewed journals. This research will also contribute to the fulfilment of a doctoral thesis (PhD). No individual participant will be identified in any report or presentation arising from the research. You will be offered the option of being sent a newsletter containing the summary results following completion of this study.

11. What if there is a problem?

The University of Oxford, as Sponsor, has appropriate insurance in place in the unlikely event that you suffer any harm as a direct consequence of your participation in this study. NHS indemnity operates in respect of the clinical treatment which is provided. If you wish to complain about any aspect of the way in which you have been approached or treated, or how your information is handled during the course of this study, you should contact **Daniel Howgate [daniel.howgate@ndorms.ox.ac.uk]**, or their supervisor **Professor Jonathan Rees [jonathan.rees@ndorms.ox.ac.uk]**, who will do their best to answer your query. The researcher should acknowledge your concern within 10 working days and give you an indication of how they intend to deal with it. You may also contact the **University of Oxford Clinical Trials and Research Governance (CTRG) office on 01865 616480, or the head of CTRG [ctrg@admin.ox.ac.uk]**.

The Patient Advisory Liaison Service (PALS) is a confidential NHS service that can provide you with support for any complaints or queries you may have regarding the care you receive as an NHS patient. PALS is unable to provide information about this research study. If you wish to contact the **PALS team**

at the Nuffield Orthopaedic Centre please call 01865738126 [PALS@ouh.nhs.uk]. If you wish to contact the **PALS team at Wycombe General Hospital please call 01296 316042 [bht.pals@.nhs.uk].**

12. Who is organising and funding the research?

This study will be run by a research team based at the Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences (NDORMs), with funding provided by the Dinwoodie Charitable Research Company, and approval from the Royal College of Surgeons (RCS) of England.

13. Who has reviewed the study?

The study has been reviewed by, and received ethical approval through the NHS Research Ethics Committee (NHS REC), and the Health Research Authority (HRA).

Further information and contact details:

If you are unsure about taking part in this study then please take some time to consider the information and ask more questions. For more information, please contact the lead researcher:

Mr Daniel Howgate MBChB, BSc (Hons), FRCS (Tr&Orth)

Royal College of Surgeons of England and Dinwoodie Research Fellow,

Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford OX3 7LD.

Email: daniel.howgate@ndorms.ox.ac.uk

Tel: 01865 737540

Thank you for considering taking part.

E.7 Consultant and Fellow Participant Consent Form

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

Study Code: *Site ID Code:* *Participant identification number:*

SURGEON PARTICIPANT CONSENT FORM: CONSULTANTS & FELLOWS

A prospective randomised controlled study assessing surgical performance and the impact of simulation training in primary THR

Name of Researcher:	*If you agree, please initial box*
1. I confirm that I have read the information sheet dated..... (version.....) for this study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.	
3. I understand that relevant sections of my anonymised data collected during the study may be looked at by individuals from University of Oxford, from regulatory authorities and from the NHS Trust(s), where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	
4. I agree to take part in this study.	

Name of Participant	*Date*	*Signature*
Name of Person taking Consent	*Date*	*Signature*

**1 copy for participant; 1 copy for researcher site file; 1 (original) to be kept in medical notes* (if participant is a patient).

E.8 Specialty Registrar Participant Consent Form

Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

Study Code: *Site ID Code:* *Participant identification number:*

SURGEON PARTICIPANT CONSENT FORM: SPECIALTY REGISTRARS

A prospective randomised controlled study assessing surgical performance and the impact of simulation training in primary THR

Name of Researcher:	*If you agree, please initial box*
1. I confirm that I have read the information sheet dated..... (version.....) for this study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.	
3. I understand that relevant sections of my anonymised data collected during the study may be looked at by individuals from University of Oxford, from regulatory authorities and from the NHS Trust(s), where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	
4. I understand that responsible members of the research team may request sections of my training data (e.g. 'logbook' or ePortfolio) and link this to my anonymized research data where it is relevant to my taking part in this research. I give permission for these individuals to use such data I provide.	
5. I agree to take part in this study.	

Name of Participant	*Date*	*Signature*

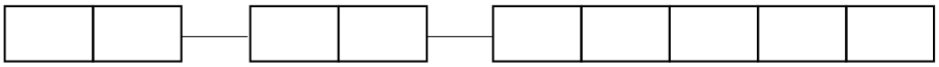
E.9 Patient Participant Consent Form





Mr Daniel Howgate
Honorary Specialty Registrar Trauma & Orthopaedic Surgery and DPhil Student
Botnar Institute of Musculoskeletal Sciences, University of Oxford, Old Road, Oxford, OX3 7LD
E-mail: daniel.howgate@ndorms.ox.ac.uk
Oxford telephone number: 01865 760063

Study Code: *Site ID Code:* *Patient identification number:*



PATIENT CONSENT FORM

THR PERFORMANCE & ASSESSMENT

Name of Researcher:	*If you agree, please initial box*
1. I confirm that I have read the information sheet dated..... (version.....) for this study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand the lead researcher and research team (supervisors or collaborators) will have access to the minimum personally-identifiable information possible. Only completely anonymised data will be used outside of NHS premises.	
3. I understand that responsible members of the University of Oxford may be given access to anonymised study records data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations.	
4. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected.	
5. I agree to take part in this study.	

_____	_____	_____
Name of Participant	*Date*	*Signature*
_____	_____	_____
Name of Person taking Consent	*Date*	*Signature*

1 copy for participant; 1 copy for researcher site file; 1 (original) to be kept in medical notes (if participant is a patient).

E.10 Oxford Hip Score

Problems with your hip

During the past 4 weeks..

✓tick one box for every question.

1. ***During the past 4 weeks*****.....**

How would you describe the pain you usually had from your hip?

None	Very mild	Mild	Moderate	Severe
❑	❑	❑	❑	❑

2. ***During the past 4 weeks*****.....**

Have you had any trouble with washing and drying yourself (all over) because of your hip?

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
❑	❑	❑	❑	❑

3. ***During the past 4 weeks*****.....**

Have you had any trouble getting in and out of a car or using public transport because of your hip? *(whichever you tend to use)*

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
❑	❑	❑	❑	❑

4. ***During the past 4 weeks*****.....**

Have you been able to put on a pair of socks, stockings or tights?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

5. ***During the past 4 weeks*****.....**

Could you do the household shopping on your own?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

6. ***During the past 4 weeks*****.....**

For how long have you been able to walk before pain from your hip becomes severe? (*with or without a stick)*

No pain/ More than 30 minutes	16 to 30 minutes	5 to 15 minutes	Around the house only	Not at all -pain severe on walking
❑	❑	❑	❑	❑

The Oxford Hip Score©Department of Public Health, University of Oxford, Old Road Campus, Oxford OX3 7LF , UK.

P.T.O./

During the past 4 weeks...

✓tick one box for every question

7 ***During the past 4 weeks*****.....**

Have you been able to climb a flight of stairs?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

8 ***During the past 4 weeks*****.....**

After a meal (sat at a table), how painful has it been for you to stand up from a chair because of your hip?

Not at all painful	Slightly painful	Moderately painful	Very painful	Unbearable
❑	❑	❑	❑	❑

9 ***During the past 4 weeks*****.....**

Have you been limping when walking, because of your hip?

Rarely/ never	Sometimes, or just at first	Often, not just at first	Most of the time	All of the time
❑	❑	❑	❑	❑

10 ***During the past 4 weeks*****.....**

Have you had any sudden, severe pain - 'shooting', 'stabbing' or 'spasms' - from the affected hip?

No days	Only 1 or 2 days	Some days	Most days	Every day
❑	❑	❑	❑	❑

11 ***During the past 4 weeks*****.....**

How much has pain from your hip interfered with your usual work *(including housework)*?

Not at all	A little bit	Moderately	Greatly	Totally
❑	❑	❑	❑	❑

12 ***During the past 4 weeks*****.....**

Have you been troubled by pain from your hip in bed at night?

No nights	Only 1 or 2 nights	Some nights	Most nights	Every night
❑	❑	❑	❑	❑

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E.11 EQ-5D-5L



Health Questionnaire

English version for the UK

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Under each heading, please tick the ONE box that best describes your health TODAY.

MOBILITY

I have no problems in walking about ❑
I have slight problems in walking about ❑
I have moderate problems in walking about ❑
I have severe problems in walking about ❑
I am unable to walk about ❑

SELF-CARE

I have no problems washing or dressing myself ❑
I have slight problems washing or dressing myself ❑
I have moderate problems washing or dressing myself ❑
I have severe problems washing or dressing myself ❑
I am unable to wash or dress myself ❑

USUAL ACTIVITIES *(e.g. work, study, housework, family or leisure activities)*

I have no problems doing my usual activities ❑
I have slight problems doing my usual activities ❑
I have moderate problems doing my usual activities ❑
I have severe problems doing my usual activities ❑
I am unable to do my usual activities ❑

PAIN / DISCOMFORT

I have no pain or discomfort ❑
I have slight pain or discomfort ❑
I have moderate pain or discomfort ❑
I have severe pain or discomfort ❑
I have extreme pain or discomfort ❑

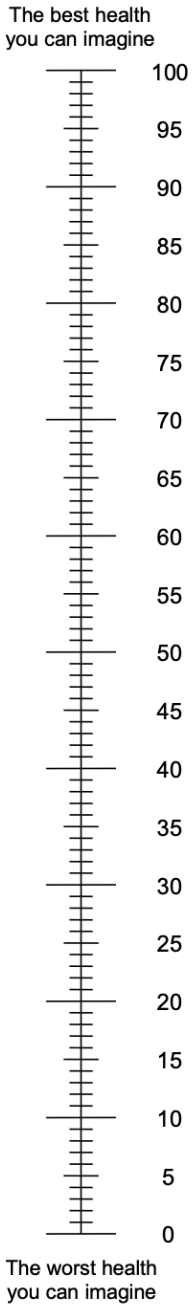
ANXIETY / DEPRESSION

I am not anxious or depressed ❑
I am slightly anxious or depressed ❑
I am moderately anxious or depressed ❑
I am severely anxious or depressed ❑
I am extremely anxious or depressed ❑

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- We would like to know how good or bad your health is TODAY.
- This scale is numbered from 0 to 100.
- 100 means the best health you can imagine.
  0 means the worst health you can imagine.
- Mark an X on the scale to indicate how your health is TODAY.
- Now, please write the number you marked on the scale in the box below.

YOUR HEALTH TODAY = ☐



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E.12 Template for recording intra-operative timings during primary THR

Start Time:	Timings			Complications		Comments
Order in List:	Start	Finish		Yes	No	IMU Sensors
Skin Incision & Surgical Approach						
Hip Dislocation						
Femoral neck osteotomy ***Saw up to head removed***						
Acetabular Preparation						
Acetabular Exposure & Labral resection ***Head removed to reamer up***						
Acetabular Reaming ***Reamer up to reamer down***						
Implant Sizing & Trialling						
Acetabular drill holes; lavage & packing						
Acetabular Component Implantation						
Cement mixing						
Acetabular cement insertion & pressurisation						
Positioning & Insertion ***Cup handling to swab in cup***						Surgeon/Assistant Impacted
Femoral Preparation						
Femoral canal broaching ***Box cut to trial reduction***						
Femoral Head Trialling ***First trial to removal of broach***						
Femoral Cementing						
Cement mixing						
Femoral canal: cement restrictor sizing; lavage, suction & packing. ***Washing & brushing to packing complete***						
Femoral canal cement insertion & pressurisation. ***Gun up to Gun down***						

Femoral Component Implantation						
Positioning & Insertion ***To trial head in situ***						
Head sizing & Trialling ***To hip reduction***						
Closure						
Capsule, Muscle, Fascia, Skin and Dressing						
TOTAL						

Study Patient identification number:

Study Surgeon Participant identification number

1. Named Orthopaedic Consultant		
2. Operation	RIGHT THR	LEFT THR
3. Fixation		
4. Date of surgery		
5. Day of Week	Monday / Tuesday / Wednesday / Thursday / Friday	

E.13 Study A: EQ-5D Domain scores.

EQ-5D 5L Domain 1

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Baseline EQ5D Mobility					
					0.12
No problems (1)	6 (3.5%)	1 (2.0%)	2 (2.7%)	3 (6.2%)	
Slight problems (2)	18 (10%)	5 (9.8%)	11 (15%)	2 (4.2%)	
Moderate problems (3)	59 (34%)	21 (41%)	26 (36%)	12 (25%)	
Severe problems (4)	80 (47%)	20 (39%)	33 (45%)	27 (56%)	
Unable to walk (5)	9 (5.2%)	4 (7.8%)	1 (1.4%)	4 (8.3%)	
Unknown	48	25	19	4	
3-month follow-up EQ5D Mobility					
					0.7
No problems (1)	77 (49%)	27 (59%)	31 (46%)	19 (43%)	
Slight problems (2)	50 (32%)	13 (28%)	23 (34%)	14 (32%)	
Moderate problems (3)	27 (17%)	5 (11%)	12 (18%)	10 (23%)	
Severe problems (4)	4 (2.5%)	1 (2.2%)	2 (2.9%)	1 (2.3%)	
Unable to walk (5)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	62	30	24	8	
Change in EQ5D Mobility					
					0.6
Improved -4 points	4 (2.5%)	3 (6.5%)	0 (0%)	1 (2.3%)	
Improved -3 points	27 (17%)	7 (15%)	11 (16%)	9 (21%)	
Improved -2 points	64 (41%)	19 (41%)	28 (41%)	17 (40%)	
Improved -1 point	37 (24%)	13 (28%)	15 (22%)	9 (21%)	
No Change	22 (14%)	4 (8.7%)	12 (18%)	6 (14%)	
Deteriorated 1 point	3 (1.9%)	0 (0%)	2 (2.9%)	1 (2.3%)	
Deteriorated 2 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 3 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	63	30	24	9	

[1] n (%)

[2] Fisher's exact test

EQ-5D 5L Domain 2

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Baseline EQ5D Self-care					
					0.3
No problems (1)	52 (30%)	16 (31%)	22 (30%)	14 (29%)	
Slight problems (2)	45 (26%)	9 (18%)	22 (30%)	14 (29%)	
Moderate problems (3)	56 (33%)	22 (43%)	22 (30%)	12 (25%)	
Severe problems (4)	16 (9.3%)	3 (5.9%)	7 (9.6%)	6 (12%)	
Unable to wash or dress (5)	3 (1.7%)	1 (2.0%)	0 (0%)	2 (4.2%)	
Unknown	48	25	19	4	
3-month follow-up EQ5D Self-care					
					0.5
No problems (1)	114 (72%)	33 (72%)	46 (68%)	35 (80%)	
Slight problems (2)	28 (18%)	7 (15%)	16 (24%)	5 (11%)	
Moderate problems (3)	15 (9.5%)	6 (13%)	5 (7.4%)	4 (9.1%)	
Severe problems (4)	1 (0.6%)	0 (0%)	1 (1.5%)	0 (0%)	
Unable to wash or dress (5)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	62	30	24	8	
Change in EQ5D Self-care					
					0.5
Improved -4 points	2 (1.3%)	1 (2.2%)	0 (0%)	1 (2.3%)	
Improved -3 points	6 (3.8%)	1 (2.2%)	2 (2.9%)	3 (7.0%)	
Improved -2 points	42 (27%)	15 (33%)	18 (26%)	9 (21%)	
Improved -1 point	40 (25%)	8 (17%)	17 (25%)	15 (35%)	
No Change	57 (36%)	17 (37%)	26 (38%)	14 (33%)	
Deteriorated 1 point	10 (6.4%)	4 (8.7%)	5 (7.4%)	1 (2.3%)	
Deteriorated 2 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 3 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	63	30	24	9	

[1] n (%)

[2] Fisher's exact test

EQ-5D 5L Domain 3

	Overall, N = 220[1]	**Consultant**, N = 76[1]	**Fellow**, N = 92[1]	**Specialty Registrar**, N = 52[1]	**p-value**
Baseline EQ5D Usual activities					
No problems (1)	9 (5.2%)	0 (0%)	6 (8.2%)	3 (6.2%)	
Slight problems (2)	23 (13%)	12 (24%)	9 (12%)	2 (4.2%)	
Moderate problems (3)	68 (40%)	18 (35%)	28 (38%)	22 (46%)	
Severe problems (4)	47 (27%)	11 (22%)	22 (30%)	14 (29%)	
Unable to do usual activities (5)	25 (15%)	10 (20%)	8 (11%)	7 (15%)	
Unknown	48	25	19	4	
3-month follow-up EQ5D Usual activities					
					0.064
No problems (1)	88 (56%)	32 (70%)	34 (50%)	22 (50%)	
Slight problems (2)	41 (26%)	7 (15%)	23 (34%)	11 (25%)	
Moderate problems (3)	24 (15%)	5 (11%)	8 (12%)	11 (25%)	
Severe problems (4)	5 (3.2%)	2 (4.3%)	3 (4.4%)	0 (0%)	
Unable to do usual activities (5)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	62	30	24	8	
Change in EQ5D Usual activities					
Improved -4 points	5 (3.2%)	4 (8.7%)	0 (0%)	1 (2.3%)	
Improved -3 points	35 (22%)	9 (20%)	16 (24%)	10 (23%)	
Improved -2 points	53 (34%)	18 (39%)	21 (31%)	14 (33%)	
Improved -1 point	38 (24%)	11 (24%)	16 (24%)	11 (26%)	
No Change	19 (12%)	2 (4.3%)	12 (18%)	5 (12%)	
Deteriorated 1 point	7 (4.5%)	2 (4.3%)	3 (4.4%)	2 (4.7%)	
Deteriorated 2 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 3 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	63	30	24	9	

[1] n (%)

EQ-5D 5L Domain 4

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Baseline EQ5D Pain/discomfort					
					0.3
No pain/discomfort (1)	1 (0.6%)	0 (0%)	0 (0%)	1 (2.1%)	
Slight pain/discomfort (2)	14 (8.1%)	3 (5.9%)	9 (12%)	2 (4.2%)	
Moderate pain/discomfort (3)	52 (30%)	18 (35%)	24 (33%)	10 (21%)	
Severe pain/discomfort (4)	75 (44%)	21 (41%)	28 (38%)	26 (54%)	
Extreme pain/discomfort (5)	30 (17%)	9 (18%)	12 (16%)	9 (19%)	
Unknown	48	25	19	4	
3-month follow-up EQ5D Pain/discomfort					
					0.8
No pain/discomfort (1)	73 (46%)	24 (52%)	30 (44%)	19 (43%)	
Slight pain/discomfort (2)	57 (36%)	14 (30%)	24 (35%)	19 (43%)	
Moderate pain/discomfort (3)	22 (14%)	7 (15%)	11 (16%)	4 (9.1%)	
Severe pain/discomfort (4)	6 (3.8%)	1 (2.2%)	3 (4.4%)	2 (4.5%)	
Extreme pain/discomfort (5)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	62	30	24	8	
Change in EQ5D Pain/discomfort					
Improved -4 points	8 (5.1%)	3 (6.5%)	5 (7.4%)	0 (0%)	
Improved -3 points	47 (30%)	12 (26%)	15 (22%)	20 (47%)	
Improved -2 points	46 (29%)	16 (35%)	19 (28%)	11 (26%)	
Improved -1 point	40 (25%)	13 (28%)	19 (28%)	8 (19%)	
No Change	15 (9.6%)	2 (4.3%)	9 (13%)	4 (9.3%)	
Deteriorated 1 point	1 (0.6%)	0 (0%)	1 (1.5%)	0 (0%)	
Deteriorated 2 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 3 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Deteriorated 4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	63	30	24	9	

[1] n (%)

[2] Fisher's exact test

EQ-5D 5L Domain 5

	Overall, N = 220[1]	Consultant, N = 76[1]	Fellow, N = 92[1]	Specialty Registrar, N = 52[1]	p-value[2]
Baseline EQ5D Anxiety/depression					
					0.5
Not anxious/depressed (1)	76 (44%)	24 (47%)	33 (45%)	19 (40%)	
Slightly anxious/depressed (2)	48 (28%)	14 (27%)	20 (27%)	14 (29%)	
Moderately anxious/depressed (3)	36 (21%)	7 (14%)	18 (25%)	11 (23%)	
Severely anxious/depressed (4)	6 (3.5%)	4 (7.8%)	1 (1.4%)	1 (2.1%)	
Extremely anxious/depressed (5)	6 (3.5%)	2 (3.9%)	1 (1.4%)	3 (6.2%)	
Unknown	48	25	19	4	
3-month follow-up EQ5D Anxiety/depression					
					0.4
Not anxious/depressed (1)	110 (70%)	31 (67%)	47 (69%)	32 (73%)	
Slightly anxious/depressed (2)	33 (21%)	11 (24%)	16 (24%)	6 (14%)	
Moderately anxious/depressed (3)	9 (5.7%)	4 (8.7%)	2 (2.9%)	3 (6.8%)	
Severely anxious/depressed (4)	5 (3.2%)	0 (0%)	2 (2.9%)	3 (6.8%)	
Extremely anxious/depressed (5)	1 (0.6%)	0 (0%)	1 (1.5%)	0 (0%)	
Unknown	62	30	24	8	
Change in EQ5D Anxiety/depression					
					0.7
Improved -4 points	1 (0.6%)	1 (2.2%)	0 (0%)	0 (0%)	
Improved -3 points	1 (0.6%)	0 (0%)	0 (0%)	1 (2.3%)	
Improved -2 points	24 (15%)	7 (15%)	11 (16%)	6 (14%)	
Improved -1 point	38 (24%)	8 (17%)	18 (26%)	12 (28%)	
No Change	82 (52%)	28 (61%)	31 (46%)	23 (53%)	
Deteriorated 1 point	8 (5.1%)	2 (4.3%)	5 (7.4%)	1 (2.3%)	
Deteriorated 2 points	2 (1.3%)	0 (0%)	2 (2.9%)	0 (0%)	
Deteriorated 3 points	1 (0.6%)	0 (0%)	1 (1.5%)	0 (0%)	
Deteriorated 4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	63	30	24	9	

[1] n (%)

[2] Fisher's exact test

E.14 Study B: Oxford Hip Scores

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline OHS					
	15 (8)	15 (7)	16 (9)	12 (5)	0.3
Unknown	4	0	0	4	
3-month follow-up OHS					
	40.1 (6.1)	35.7 (7.0)	40.3 (6.1)	42.9 (3.2)	0.13
Unknown	8	2	1	5	
Change in OHS					
	25 (9)	21 (10)	24 (9)	32 (6)	0.061
Unknown	9	2	2	5	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline OHS					
	15 (8)	17 (7)	15 (10)	12 (5)	0.2
Unknown	4	0	0	4	
3-month follow-up OHS					
	40.1 (6.1)	38.5 (7.2)	40.0 (6.0)	42.9 (3.2)	0.4
Unknown	8	2	1	5	
Change in OHS					
	25 (9)	22 (10)	25 (8)	32 (6)	0.055
Unknown	9	2	2	5	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline OHS					
	15 (8)	14 (6)	18 (8)	13 (8)	0.077
3-month follow-up OHS					
	40.1 (6.2)	35.6 (8.3)	38.6 (6.3)	42.9 (4.2)	0.061
Unknown	4	1	1	2	
Change in OHS					
	25 (9)	21 (11)	21 (8)	31 (5)	**0.004**
Unknown	5	1	1	3	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

E.15 Study B: EQ-5D 5L Visual Analogue Score (VAS)

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D VAS					
	57 (22)	67 (20)	55 (23)	53 (22)	0.4
Unknown	4	0	0	4	
3-month follow-up EQ5D VAS					
	75 (18)	83 (14)	75 (18)	69 (18)	0.3
Unknown	8	2	1	5	
Change in EQ5D VAS					
	19 (15)	21 (13)	20 (16)	15 (14)	0.8
Unknown	8	2	1	5	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D VAS					
	57 (22)	65 (20)	53 (24)	53 (22)	0.3
Unknown	4	0	0	4	
3-month follow-up EQ5D VAS					
	75 (18)	82 (13)	73 (19)	69 (18)	0.2
Unknown	8	2	1	5	
Change in EQ5D VAS					
	19 (15)	20 (13)	20 (17)	15 (14)	0.9
Unknown	8	2	1	5	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D VAS					
	55 (22)	56 (14)	53 (23)	57 (25)	0.8
3-month follow-up EQ5D VAS					
	74 (17)	77 (13)	72 (19)	74 (18)	0.8
Unknown	4	1	1	2	
Change in EQ5D VAS					
	20 (15)	26 (11)	21 (16)	17 (16)	0.4
Unknown	4	1	1	2	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

E.16 Study B: EQ-5D 5L Domain 1

Relation to StR group

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline EQ5D Mobility				
				0.012
No problems (1)	3 (6.2%)	0 (0%)	3 (11%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (7.4%)	
Moderate problems (3)	12 (25%)	9 (43%)	3 (11%)	
Severe problems (4)	27 (56%)	12 (57%)	15 (56%)	
Unable to walk (5)	4 (8.3%)	0 (0%)	4 (15%)	
Unknown	4	4	0	
3-month follow-up EQ5D Mobility				
				0.5
No problems (1)	19 (43%)	8 (42%)	11 (44%)	
Slight problems (2)	14 (32%)	7 (37%)	7 (28%)	
Moderate problems (3)	10 (23%)	3 (16%)	7 (28%)	
Severe problems (4)	1 (2.3%)	1 (5.3%)	0 (0%)	
Unknown	8	6	2	
Change in EQ5D Mobility				
				>0.9
Improved -4 points	1 (2.3%)	0 (0%)	1 (4.2%)	
Improved -3 points	9 (21%)	4 (21%)	5 (21%)	
Improved -2 points	17 (40%)	8 (42%)	9 (38%)	
Improved -1 point	9 (21%)	4 (21%)	5 (21%)	
No Change	6 (14%)	3 (16%)	3 (12%)	
Deteriorated 1 point	1 (2.3%)	0 (0%)	1 (4.2%)	
Unknown	9	6	3	

[1] n (%)

[2] Fisher's exact test

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D Mobility					
					>0.9
No problems (1)	3 (6.2%)	0 (0%)	3 (10%)	0 (0%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (6.7%)	0 (0%)	
Moderate problems (3)	12 (25%)	3 (33%)	7 (23%)	2 (22%)	
Severe problems (4)	27 (56%)	5 (56%)	15 (50%)	7 (78%)	
Unable to walk (5)	4 (8.3%)	1 (11%)	3 (10%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Mobility					
					0.021
No problems (1)	19 (43%)	1 (14%)	16 (55%)	2 (25%)	
Slight problems (2)	14 (32%)	1 (14%)	8 (28%)	5 (62%)	
Moderate problems (3)	10 (23%)	4 (57%)	5 (17%)	1 (12%)	
Severe problems (4)	1 (2.3%)	1 (14%)	0 (0%)	0 (0%)	
Unknown	8	2	1	5	
Change in EQ5D Mobility					
					0.5
Improved -4 points	1 (2.3%)	0 (0%)	1 (3.6%)	0 (0%)	
Improved -3 points	9 (21%)	0 (0%)	7 (25%)	2 (25%)	
Improved -2 points	17 (40%)	3 (43%)	11 (39%)	3 (38%)	
Improved -1 point	9 (21%)	1 (14%)	5 (18%)	3 (38%)	
No Change	6 (14%)	3 (43%)	3 (11%)	0 (0%)	
Deteriorated 1 point	1 (2.3%)	0 (0%)	1 (3.6%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D Mobility					
					0.077
No problems (1)	3 (6.2%)	0 (0%)	3 (13%)	0 (0%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (8.7%)	0 (0%)	
Moderate problems (3)	12 (25%)	8 (50%)	2 (8.7%)	2 (22%)	
Severe problems (4)	27 (56%)	7 (44%)	13 (57%)	7 (78%)	
Unable to walk (5)	4 (8.3%)	1 (6.2%)	3 (13%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Mobility					
					0.2
No problems (1)	19 (43%)	6 (43%)	11 (50%)	2 (25%)	
Slight problems (2)	14 (32%)	2 (14%)	7 (32%)	5 (62%)	
Moderate problems (3)	10 (23%)	5 (36%)	4 (18%)	1 (12%)	
Severe problems (4)	1 (2.3%)	1 (7.1%)	0 (0%)	0 (0%)	
Unknown	8	2	1	5	
Change in EQ5D Mobility					
					0.8
Improved -4 points	1 (2.3%)	0 (0%)	1 (4.8%)	0 (0%)	
Improved -3 points	9 (21%)	2 (14%)	5 (24%)	2 (25%)	
Improved -2 points	17 (40%)	6 (43%)	8 (38%)	3 (38%)	
Improved -1 point	9 (21%)	2 (14%)	4 (19%)	3 (38%)	
No Change	6 (14%)	4 (29%)	2 (9.5%)	0 (0%)	
Deteriorated 1 point	1 (2.3%)	0 (0%)	1 (4.8%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D Mobility					
					0.6
No problems (1)	3 (7.1%)	0 (0%)	1 (5.9%)	2 (11%)	
Slight problems (2)	2 (4.8%)	0 (0%)	2 (12%)	0 (0%)	
Moderate problems (3)	9 (21%)	2 (33%)	3 (18%)	4 (21%)	
Severe problems (4)	25 (60%)	4 (67%)	11 (65%)	10 (53%)	
Unable to walk (5)	3 (7.1%)	0 (0%)	0 (0%)	3 (16%)	
3-month follow-up EQ5D Mobility					
					0.3
No problems (1)	16 (42%)	1 (20%)	6 (38%)	9 (53%)	
Slight problems (2)	13 (34%)	1 (20%)	6 (38%)	6 (35%)	
Moderate problems (3)	8 (21%)	2 (40%)	4 (25%)	2 (12%)	
Severe problems (4)	1 (2.6%)	1 (20%)	0 (0%)	0 (0%)	
Unknown	4	1	1	2	
Change in EQ5D Mobility					
					0.8
Improved -4 points	1 (2.7%)	0 (0%)	0 (0%)	1 (6.2%)	
Improved -3 points	7 (19%)	0 (0%)	3 (19%)	4 (25%)	
Improved -2 points	15 (41%)	2 (40%)	6 (38%)	7 (44%)	
Improved -1 point	8 (22%)	1 (20%)	4 (25%)	3 (19%)	
No Change	5 (14%)	2 (40%)	2 (12%)	1 (6.2%)	
Deteriorated 1 point	1 (2.7%)	0 (0%)	1 (6.2%)	0 (0%)	
Unknown	5	1	1	3	

[1] n (%)

[2] Fisher's exact test

E.17 Study B: EQ-5D 5L Domain 2

Relation to StR group

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline EQ5D Self-care				
				0.2
No problems (1)	14 (29%)	4 (19%)	10 (37%)	
Slight problems (2)	14 (29%)	6 (29%)	8 (30%)	
Moderate problems (3)	12 (25%)	6 (29%)	6 (22%)	
Severe problems (4)	6 (12%)	5 (24%)	1 (3.7%)	
Unable to wash or dress (5)	2 (4.2%)	0 (0%)	2 (7.4%)	
Unknown	4	4	0	
3-month follow-up EQ5D Self-care				
				0.013
No problems (1)	35 (80%)	12 (63%)	23 (92%)	
Slight problems (2)	5 (11%)	5 (26%)	0 (0%)	
Moderate problems (3)	4 (9.1%)	2 (11%)	2 (8.0%)	
Unknown	8	6	2	
Change in EQ5D Self-care				
				0.8
Improved -4 points	1 (2.3%)	0 (0%)	1 (4.2%)	
Improved -3 points	3 (7.0%)	2 (11%)	1 (4.2%)	
Improved -2 points	9 (21%)	4 (21%)	5 (21%)	
Improved -1 point	15 (35%)	7 (37%)	8 (33%)	
No Change	14 (33%)	5 (26%)	9 (38%)	
Deteriorated 1 point	1 (2.3%)	1 (5.3%)	0 (0%)	
Unknown	9	6	3	

[1] n (%)

[2] Fisher's exact test

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D Self-care					
					0.022
No problems (1)	14 (29%)	5 (56%)	9 (30%)	0 (0%)	
Slight problems (2)	14 (29%)	2 (22%)	11 (37%)	1 (11%)	
Moderate problems (3)	12 (25%)	2 (22%)	6 (20%)	4 (44%)	
Severe problems (4)	6 (12%)	0 (0%)	2 (6.7%)	4 (44%)	
Unable to wash or dress (5)	2 (4.2%)	0 (0%)	2 (6.7%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Self-care					
					0.2
No problems (1)	35 (80%)	5 (71%)	25 (86%)	5 (62%)	
Slight problems (2)	5 (11%)	2 (29%)	2 (6.9%)	1 (12%)	
Moderate problems (3)	4 (9.1%)	0 (0%)	2 (6.9%)	2 (25%)	
Unknown	8	2	1	5	
Change in EQ5D Self-care					
					0.084
Improved -4 points	1 (2.3%)	0 (0%)	1 (3.6%)	0 (0%)	
Improved -3 points	3 (7.0%)	0 (0%)	2 (7.1%)	1 (12%)	
Improved -2 points	9 (21%)	1 (14%)	4 (14%)	4 (50%)	
Improved -1 point	15 (35%)	1 (14%)	11 (39%)	3 (38%)	
No Change	14 (33%)	4 (57%)	10 (36%)	0 (0%)	
Deteriorated 1 point	1 (2.3%)	1 (14%)	0 (0%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D Self-care					
					0.031
No problems (1)	14 (29%)	7 (44%)	7 (30%)	0 (0%)	
Slight problems (2)	14 (29%)	5 (31%)	8 (35%)	1 (11%)	
Moderate problems (3)	12 (25%)	3 (19%)	5 (22%)	4 (44%)	
Severe problems (4)	6 (12%)	1 (6.2%)	1 (4.3%)	4 (44%)	
Unable to wash or dress (5)	2 (4.2%)	0 (0%)	2 (8.7%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Self-care					
					0.017
No problems (1)	35 (80%)	10 (71%)	20 (91%)	5 (62%)	
Slight problems (2)	5 (11%)	4 (29%)	0 (0%)	1 (12%)	
Moderate problems (3)	4 (9.1%)	0 (0%)	2 (9.1%)	2 (25%)	
Unknown	8	2	1	5	
Change in EQ5D Self-care					
					0.15
Improved -4 points	1 (2.3%)	0 (0%)	1 (4.8%)	0 (0%)	
Improved -3 points	3 (7.0%)	1 (7.1%)	1 (4.8%)	1 (12%)	
Improved -2 points	9 (21%)	1 (7.1%)	4 (19%)	4 (50%)	
Improved -1 point	15 (35%)	4 (29%)	8 (38%)	3 (38%)	
No Change	14 (33%)	7 (50%)	7 (33%)	0 (0%)	
Deteriorated 1 point	1 (2.3%)	1 (7.1%)	0 (0%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D Self-care					
					0.10
No problems (1)	11 (26%)	3 (50%)	6 (35%)	2 (11%)	
Slight problems (2)	13 (31%)	2 (33%)	7 (41%)	4 (21%)	
Moderate problems (3)	11 (26%)	1 (17%)	3 (18%)	7 (37%)	
Severe problems (4)	5 (12%)	0 (0%)	0 (0%)	5 (26%)	
Unable to wash or dress (5)	2 (4.8%)	0 (0%)	1 (5.9%)	1 (5.3%)	
3-month follow-up EQ5D Self-care					
					0.3
No problems (1)	29 (76%)	3 (60%)	13 (81%)	13 (76%)	
Slight problems (2)	5 (13%)	2 (40%)	2 (12%)	1 (5.9%)	
Moderate problems (3)	4 (11%)	0 (0%)	1 (6.2%)	3 (18%)	
Unknown	4	1	1	2	
Change in EQ5D Self-care					
					0.005
Improved -4 points	1 (2.7%)	0 (0%)	1 (6.2%)	0 (0%)	
Improved -3 points	2 (5.4%)	0 (0%)	0 (0%)	2 (12%)	
Improved -2 points	8 (22%)	0 (0%)	1 (6.2%)	7 (44%)	
Improved -1 point	14 (38%)	1 (20%)	7 (44%)	6 (38%)	
No Change	11 (30%)	3 (60%)	7 (44%)	1 (6.2%)	
Deteriorated 1 point	1 (2.7%)	1 (20%)	0 (0%)	0 (0%)	
Unknown	5	1	1	3	

[1] n (%)

[2] Fisher's exact test

E.18 Study B: EQ-5D 5L Domain 3

Relation to StR group

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline EQ5D Usual activities				
				0.7
No problems (1)	3 (6.2%)	1 (4.8%)	2 (7.4%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (7.4%)	
Moderate problems (3)	22 (46%)	11 (52%)	11 (41%)	
Severe problems (4)	14 (29%)	7 (33%)	7 (26%)	
Unable to do usual activities (5)	7 (15%)	2 (9.5%)	5 (19%)	
Unknown	4	4	0	
3-month follow-up EQ5D Usual activities				
				0.9
No problems (1)	22 (50%)	10 (53%)	12 (48%)	
Slight problems (2)	11 (25%)	5 (26%)	6 (24%)	
Moderate problems (3)	11 (25%)	4 (21%)	7 (28%)	
Unknown	8	6	2	
Change in EQ5D Usual activities				
				>0.9
Improved -4 points	1 (2.3%)	1 (5.3%)	0 (0%)	
Improved -3 points	10 (23%)	5 (26%)	5 (21%)	
Improved -2 points	14 (33%)	5 (26%)	9 (38%)	
Improved -1 point	11 (26%)	5 (26%)	6 (25%)	
No Change	5 (12%)	2 (11%)	3 (12%)	
Deteriorated 1 point	2 (4.7%)	1 (5.3%)	1 (4.2%)	
Unknown	9	6	3	

[1] n (%)

[2] Fisher's exact test

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D Usual activities					
					0.6
No problems (1)	3 (6.2%)	1 (11%)	2 (6.7%)	0 (0%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (6.7%)	0 (0%)	
Moderate problems (3)	22 (46%)	5 (56%)	13 (43%)	4 (44%)	
Severe problems (4)	14 (29%)	1 (11%)	8 (27%)	5 (56%)	
Unable to do usual activities (5)	7 (15%)	2 (22%)	5 (17%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Usual activities					
					0.9
No problems (1)	22 (50%)	3 (43%)	16 (55%)	3 (38%)	
Slight problems (2)	11 (25%)	2 (29%)	7 (24%)	2 (25%)	
Moderate problems (3)	11 (25%)	2 (29%)	6 (21%)	3 (38%)	
Unknown	8	2	1	5	
Change in EQ5D Usual activities					
					0.6
Improved -4 points	1 (2.3%)	0 (0%)	1 (3.6%)	0 (0%)	
Improved -3 points	10 (23%)	2 (29%)	6 (21%)	2 (25%)	
Improved -2 points	14 (33%)	3 (43%)	10 (36%)	1 (12%)	
Improved -1 point	11 (26%)	0 (0%)	7 (25%)	4 (50%)	
No Change	5 (12%)	1 (14%)	3 (11%)	1 (12%)	
Deteriorated 1 point	2 (4.7%)	1 (14%)	1 (3.6%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D Usual activities					
					0.3
No problems (1)	3 (6.2%)	2 (12%)	1 (4.3%)	0 (0%)	
Slight problems (2)	2 (4.2%)	0 (0%)	2 (8.7%)	0 (0%)	
Moderate problems (3)	22 (46%)	9 (56%)	9 (39%)	4 (44%)	
Severe problems (4)	14 (29%)	2 (12%)	7 (30%)	5 (56%)	
Unable to do usual activities (5)	7 (15%)	3 (19%)	4 (17%)	0 (0%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Usual activities					
					>0.9
No problems (1)	22 (50%)	7 (50%)	12 (55%)	3 (38%)	
Slight problems (2)	11 (25%)	4 (29%)	5 (23%)	2 (25%)	
Moderate problems (3)	11 (25%)	3 (21%)	5 (23%)	3 (38%)	
Unknown	8	2	1	5	
Change in EQ5D Usual activities					
					0.3
Improved -4 points	1 (2.3%)	1 (7.1%)	0 (0%)	0 (0%)	
Improved -3 points	10 (23%)	3 (21%)	5 (24%)	2 (25%)	
Improved -2 points	14 (33%)	5 (36%)	8 (38%)	1 (12%)	
Improved -1 point	11 (26%)	1 (7.1%)	6 (29%)	4 (50%)	
No Change	5 (12%)	2 (14%)	2 (9.5%)	1 (12%)	
Deteriorated 1 point	2 (4.7%)	2 (14%)	0 (0%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D Usual activities					
					0.7
No problems (1)	1 (2.4%)	0 (0%)	1 (5.9%)	0 (0%)	
Slight problems (2)	2 (4.8%)	0 (0%)	0 (0%)	2 (11%)	
Moderate problems (3)	20 (48%)	4 (67%)	9 (53%)	7 (37%)	
Severe problems (4)	14 (33%)	1 (17%)	5 (29%)	8 (42%)	
Unable to do usual activities (5)	5 (12%)	1 (17%)	2 (12%)	2 (11%)	
3-month follow-up EQ5D Usual activities					
					0.8
No problems (1)	19 (50%)	3 (60%)	6 (38%)	10 (59%)	
Slight problems (2)	9 (24%)	1 (20%)	5 (31%)	3 (18%)	
Moderate problems (3)	10 (26%)	1 (20%)	5 (31%)	4 (24%)	
Unknown	4	1	1	2	
Change in EQ5D Usual activities					
					0.6
Improved -4 points	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Improved -3 points	10 (27%)	2 (40%)	4 (25%)	4 (25%)	
Improved -2 points	11 (30%)	2 (40%)	3 (19%)	6 (38%)	
Improved -1 point	11 (30%)	0 (0%)	6 (38%)	5 (31%)	
No Change	5 (14%)	1 (20%)	3 (19%)	1 (6.2%)	
Deteriorated 1 point	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Unknown	5	1	1	3	

[1] n (%)

[2] Fisher's exact test

E.19 Study B: EQ-5D 5L Domain 4

Relation to StR group

	Overall, N = 52[1]	**Simulation training**, N = 25[1]	**Control**, N = 27[1]	**p-value**[2]
Baseline EQ5D Pain/discomfort				
				0.4
No pain/discomfort (1)	1 (2.1%)	1 (4.8%)	0 (0%)	
Slight pain/discomfort (2)	2 (4.2%)	0 (0%)	2 (7.4%)	
Moderate pain/discomfort (3)	10 (21%)	6 (29%)	4 (15%)	
Severe pain/discomfort (4)	26 (54%)	11 (52%)	15 (56%)	
Extreme pain/discomfort (5)	9 (19%)	3 (14%)	6 (22%)	
Unknown	4	4	0	
3-month follow-up EQ5D Pain/discomfort				
				0.2
No pain/discomfort (1)	19 (43%)	11 (58%)	8 (32%)	
Slight pain/discomfort (2)	19 (43%)	6 (32%)	13 (52%)	
Moderate pain/discomfort (3)	4 (9.1%)	2 (11%)	2 (8.0%)	
Severe pain/discomfort (4)	2 (4.5%)	0 (0%)	2 (8.0%)	
Unknown	8	6	2	
Change in EQ5D Pain/discomfort				
				0.6
Improved -3 points	20 (47%)	10 (53%)	10 (42%)	
Improved -2 points	11 (26%)	3 (16%)	8 (33%)	
Improved -1 point	8 (19%)	4 (21%)	4 (17%)	
No Change	4 (9.3%)	2 (11%)	2 (8.3%)	
Unknown	9	6	3	

[1] n (%)

[2] Fisher's exact test

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D Pain/discomfort					
					0.7
No pain/discomfort (1)	1 (2.1%)	0 (0%)	1 (3.3%)	0 (0%)	
Slight pain/discomfort (2)	2 (4.2%)	0 (0%)	2 (6.7%)	0 (0%)	
Moderate pain/discomfort (3)	10 (21%)	3 (33%)	6 (20%)	1 (11%)	
Severe pain/discomfort (4)	26 (54%)	6 (67%)	15 (50%)	5 (56%)	
Extreme pain/discomfort (5)	9 (19%)	0 (0%)	6 (20%)	3 (33%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Pain/discomfort					
					0.7
No pain/discomfort (1)	19 (43%)	3 (43%)	12 (41%)	4 (50%)	
Slight pain/discomfort (2)	19 (43%)	2 (29%)	14 (48%)	3 (38%)	
Moderate pain/discomfort (3)	4 (9.1%)	1 (14%)	2 (6.9%)	1 (12%)	
Severe pain/discomfort (4)	2 (4.5%)	1 (14%)	1 (3.4%)	0 (0%)	
Unknown	8	2	1	5	
Change in EQ5D Pain/discomfort					
					0.7
Improved -3 points	20 (47%)	2 (29%)	13 (46%)	5 (62%)	
Improved -2 points	11 (26%)	2 (29%)	7 (25%)	2 (25%)	
Improved -1 point	8 (19%)	1 (14%)	6 (21%)	1 (12%)	
No Change	4 (9.3%)	2 (29%)	2 (7.1%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D Pain/discomfort					
					0.088
No pain/discomfort (1)	1 (2.1%)	1 (6.2%)	0 (0%)	0 (0%)	
Slight pain/discomfort (2)	2 (4.2%)	0 (0%)	2 (8.7%)	0 (0%)	
Moderate pain/discomfort (3)	10 (21%)	6 (38%)	3 (13%)	1 (11%)	
Severe pain/discomfort (4)	26 (54%)	9 (56%)	12 (52%)	5 (56%)	
Extreme pain/discomfort (5)	9 (19%)	0 (0%)	6 (26%)	3 (33%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Pain/discomfort					
					0.7
No pain/discomfort (1)	19 (43%)	8 (57%)	7 (32%)	4 (50%)	
Slight pain/discomfort (2)	19 (43%)	4 (29%)	12 (55%)	3 (38%)	
Moderate pain/discomfort (3)	4 (9.1%)	1 (7.1%)	2 (9.1%)	1 (12%)	
Severe pain/discomfort (4)	2 (4.5%)	1 (7.1%)	1 (4.5%)	0 (0%)	
Unknown	8	2	1	5	
Change in EQ5D Pain/discomfort					
					0.7
Improved -3 points	20 (47%)	5 (36%)	10 (48%)	5 (62%)	
Improved -2 points	11 (26%)	3 (21%)	6 (29%)	2 (25%)	
Improved -1 point	8 (19%)	3 (21%)	4 (19%)	1 (12%)	
No Change	4 (9.3%)	3 (21%)	1 (4.8%)	0 (0%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D Pain/discomfort					
					0.3
No pain/discomfort (1)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Slight pain/discomfort (2)	2 (4.8%)	0 (0%)	1 (5.9%)	1 (5.3%)	
Moderate pain/discomfort (3)	8 (19%)	2 (33%)	5 (29%)	1 (5.3%)	
Severe pain/discomfort (4)	24 (57%)	4 (67%)	8 (47%)	12 (63%)	
Extreme pain/discomfort (5)	8 (19%)	0 (0%)	3 (18%)	5 (26%)	
3-month follow-up EQ5D Pain/discomfort					
					0.5
No pain/discomfort (1)	16 (42%)	2 (40%)	6 (38%)	8 (47%)	
Slight pain/discomfort (2)	16 (42%)	1 (20%)	8 (50%)	7 (41%)	
Moderate pain/discomfort (3)	4 (11%)	1 (20%)	2 (12%)	1 (5.9%)	
Severe pain/discomfort (4)	2 (5.3%)	1 (20%)	0 (0%)	1 (5.9%)	
Unknown	4	1	1	2	
Change in EQ5D Pain/discomfort					
					0.2
Improved -3 points	18 (49%)	2 (40%)	6 (38%)	10 (62%)	
Improved -2 points	9 (24%)	0 (0%)	5 (31%)	4 (25%)	
Improved -1 point	7 (19%)	1 (20%)	4 (25%)	2 (12%)	
No Change	3 (8.1%)	2 (40%)	1 (6.2%)	0 (0%)	
Unknown	5	1	1	3	

[1] n (%)

[2] Fisher's exact test

E.20 Study B: EQ-5D 5L Domain 5

Relation to StR group

	Overall, N = 52[1]	Simulation training, N = 25[1]	Control, N = 27[1]	p-value[2]
Baseline EQ5D Anxiety/depression				
				0.065
Not anxious/depressed (1)	19 (40%)	8 (38%)	11 (41%)	
Slightly anxious/depressed (2)	14 (29%)	3 (14%)	11 (41%)	
Moderately anxious/depressed (3)	11 (23%)	8 (38%)	3 (11%)	
Severely anxious/depressed (4)	1 (2.1%)	1 (4.8%)	0 (0%)	
Extremely anxious/depressed (5)	3 (6.2%)	1 (4.8%)	2 (7.4%)	
Unknown	4	4	0	
3-month follow-up EQ5D Anxiety/depression				
				0.8
Not anxious/depressed (1)	32 (73%)	13 (68%)	19 (76%)	
Slightly anxious/depressed (2)	6 (14%)	3 (16%)	3 (12%)	
Moderately anxious/depressed (3)	3 (6.8%)	2 (11%)	1 (4.0%)	
Severely anxious/depressed (4)	3 (6.8%)	1 (5.3%)	2 (8.0%)	
Unknown	8	6	2	
Change in EQ5D Anxiety/depression				
				0.054
Improved -3 points	1 (2.3%)	1 (5.3%)	0 (0%)	
Improved -2 points	6 (14%)	5 (26%)	1 (4.2%)	
Improved -1 point	12 (28%)	3 (16%)	9 (38%)	
No Change	23 (53%)	9 (47%)	14 (58%)	
Deteriorated 1 point	1 (2.3%)	1 (5.3%)	0 (0%)	
Unknown	9	6	3	

[1] n (%)

[2] Fisher's exact test

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Baseline EQ5D Anxiety/depression					
					0.001
Not anxious/depressed (1)	19 (40%)	8 (89%)	11 (37%)	0 (0%)	
Slightly anxious/depressed (2)	14 (29%)	1 (11%)	11 (37%)	2 (22%)	
Moderately anxious/depressed (3)	11 (23%)	0 (0%)	5 (17%)	6 (67%)	
Severely anxious/depressed (4)	1 (2.1%)	0 (0%)	1 (3.3%)	0 (0%)	
Extremely anxious/depressed (5)	3 (6.2%)	0 (0%)	2 (6.7%)	1 (11%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Anxiety/depression					
					0.14
Not anxious/depressed (1)	32 (73%)	7 (100%)	22 (76%)	3 (38%)	
Slightly anxious/depressed (2)	6 (14%)	0 (0%)	4 (14%)	2 (25%)	
Moderately anxious/depressed (3)	3 (6.8%)	0 (0%)	1 (3.4%)	2 (25%)	
Severely anxious/depressed (4)	3 (6.8%)	0 (0%)	2 (6.9%)	1 (12%)	
Unknown	8	2	1	5	
Change in EQ5D Anxiety/depression					
					0.013
Improved -3 points	1 (2.3%)	0 (0%)	1 (3.6%)	0 (0%)	
Improved -2 points	6 (14%)	0 (0%)	3 (11%)	3 (38%)	
Improved -1 point	12 (28%)	0 (0%)	9 (32%)	3 (38%)	
No Change	23 (53%)	7 (100%)	15 (54%)	1 (12%)	
Deteriorated 1 point	1 (2.3%)	0 (0%)	0 (0%)	1 (12%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Baseline EQ5D Anxiety/depression					
					<0.001
Not anxious/depressed (1)	19 (40%)	11 (69%)	8 (35%)	0 (0%)	
Slightly anxious/depressed (2)	14 (29%)	2 (12%)	10 (43%)	2 (22%)	
Moderately anxious/depressed (3)	11 (23%)	2 (12%)	3 (13%)	6 (67%)	
Severely anxious/depressed (4)	1 (2.1%)	1 (6.2%)	0 (0%)	0 (0%)	
Extremely anxious/depressed (5)	3 (6.2%)	0 (0%)	2 (8.7%)	1 (11%)	
Unknown	4	0	0	4	
3-month follow-up EQ5D Anxiety/depression					
					0.10
Not anxious/depressed (1)	32 (73%)	13 (93%)	16 (73%)	3 (38%)	
Slightly anxious/depressed (2)	6 (14%)	1 (7.1%)	3 (14%)	2 (25%)	
Moderately anxious/depressed (3)	3 (6.8%)	0 (0%)	1 (4.5%)	2 (25%)	
Severely anxious/depressed (4)	3 (6.8%)	0 (0%)	2 (9.1%)	1 (12%)	
Unknown	8	2	1	5	
Change in EQ5D Anxiety/depression					
					<0.001
Improved -3 points	1 (2.3%)	1 (7.1%)	0 (0%)	0 (0%)	
Improved -2 points	6 (14%)	2 (14%)	1 (4.8%)	3 (38%)	
Improved -1 point	12 (28%)	0 (0%)	9 (43%)	3 (38%)	
No Change	23 (53%)	11 (79%)	11 (52%)	1 (12%)	
Deteriorated 1 point	1 (2.3%)	0 (0%)	0 (0%)	1 (12%)	
Unknown	9	2	2	5	

[1] n (%)

[2] Fisher's exact test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Baseline EQ5D Anxiety/depression					
					0.045
Not anxious/depressed (1)	15 (36%)	6 (100%)	5 (29%)	4 (21%)	
Slightly anxious/depressed (2)	13 (31%)	0 (0%)	7 (41%)	6 (32%)	
Moderately anxious/depressed (3)	10 (24%)	0 (0%)	3 (18%)	7 (37%)	
Severely anxious/depressed (4)	1 (2.4%)	0 (0%)	1 (5.9%)	0 (0%)	
Extremely anxious/depressed (5)	3 (7.1%)	0 (0%)	1 (5.9%)	2 (11%)	
3-month follow-up EQ5D Anxiety/depression					
					>0.9
Not anxious/depressed (1)	27 (71%)	5 (100%)	11 (69%)	11 (65%)	
Slightly anxious/depressed (2)	5 (13%)	0 (0%)	3 (19%)	2 (12%)	
Moderately anxious/depressed (3)	3 (7.9%)	0 (0%)	1 (6.2%)	2 (12%)	
Severely anxious/depressed (4)	3 (7.9%)	0 (0%)	1 (6.2%)	2 (12%)	
Unknown	4	1	1	2	
Change in EQ5D Anxiety/depression					
					0.2
Improved -3 points	1 (2.7%)	0 (0%)	1 (6.2%)	0 (0%)	
Improved -2 points	5 (14%)	0 (0%)	1 (6.2%)	4 (25%)	
Improved -1 point	12 (32%)	0 (0%)	6 (38%)	6 (38%)	
No Change	18 (49%)	5 (100%)	8 (50%)	5 (31%)	
Deteriorated 1 point	1 (2.7%)	0 (0%)	0 (0%)	1 (6.2%)	
Unknown	5	1	1	3	

[1] n (%)

[2] Fisher's exact test

E.21 Study B: Radiographic parameters

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Acetabular Cup Inclination (degrees)					
	42.7 (7.2)	43.0 (9.6)	43.6 (7.0)	39.2 (4.4)	0.15
Unknown	4	0	0	4	
Acetabular Cup Anteversion (degrees)					
	16.6 (7.5)	12.6 (9.5)	17.5 (6.7)	17.3 (7.6)	0.2
Unknown	4	0	0	4	
Radiological Leg Length Discrepancy (mm)					
	2.4 (5.8)	4.2 (6.2)	2.2 (5.4)	1.3 (6.9)	0.4
Unknown	5	0	1	4	
Radiological Femoral Stem Alignment (degrees)					
	1.2 (1.7)	0.9 (0.8)	1.5 (1.9)	0.4 (1.5)	0.4
Unknown	4	0	0	4	
Barrack & Harris Femoral Cementation Grade					
					0.9
A	7 (18%)	1 (11%)	5 (21%)	1 (17%)	
B	25 (64%)	6 (67%)	14 (58%)	5 (83%)	
C	7 (18%)	2 (22%)	5 (21%)	0 (0%)	
Unknown	13	0	6	7	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Acetabular Cup Inclination (degrees)					
	42.7 (7.2)	45.0 (8.2)	42.4 (7.0)	39.2 (4.4)	0.14
Unknown	4	0	0	4	
Acetabular Cup Anteversion (degrees)					
	16.6 (7.5)	15.7 (8.3)	16.8 (7.2)	17.3 (7.6)	0.9
Unknown	4	0	0	4	
Radiological Leg Length Discrepancy (mm)					
	2.4 (5.8)	4.0 (5.3)	1.7 (5.8)	1.3 (6.9)	0.4
Unknown	5	0	1	4	
Radiological Femoral Stem Alignment (degrees)					
	1.2 (1.7)	1.3 (2.1)	1.4 (1.4)	0.4 (1.5)	0.3
Unknown	4	0	0	4	
Barrack & Harris Femoral Cementation Grade					
					0.8
A	7 (18%)	3 (19%)	3 (18%)	1 (17%)	
B	25 (64%)	9 (56%)	11 (65%)	5 (83%)	
C	7 (18%)	4 (25%)	3 (18%)	0 (0%)	
Unknown	13	0	6	7	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Acetabular Cup Inclination (degrees)					
	42.1 (6.6)	42.1 (8.6)	43.5 (6.9)	40.8 (5.7)	0.2
Acetabular Cup Anteversion (degrees)					
	16.7 (7.5)	14.7 (10.2)	17.0 (7.2)	17.1 (7.1)	0.7
Radiological Leg Length Discrepancy (mm)					
	2.1 (6.0)	4.8 (7.0)	1.0 (5.4)	2.1 (6.1)	0.3
Unknown	1	0	1	0	
Radiological Femoral Stem Alignment (degrees)					
	1.3 (1.7)	1.2 (0.9)	1.6 (1.9)	1.0 (1.8)	0.7
Barrack & Harris Femoral Cementation Grade					
					>0.9
A	6 (18%)	1 (17%)	3 (19%)	2 (18%)	
B	22 (67%)	5 (83%)	10 (62%)	7 (64%)	
C	5 (15%)	0 (0%)	3 (19%)	2 (18%)	
Unknown	9	0	1	8	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

E.22 Study B: Blood loss and transfusion requirements

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Pre-op Hb (g/dL)					
	133 (15)	134 (14)	133 (16)	131 (14)	0.9
Unknown	4	0	0	4	
Post-op Hb (g/dL)					
	109 (16)	111 (13)	108 (17)	110 (17)	0.7
Unknown	6	0	2	4	
Change in Hb (g/dL)					
	-24 (10)	-23 (7)	-25 (11)	-20 (9)	0.4
Unknown	6	0	2	4	
On-Table Blood Loss					
	304 (161)	313 (171)	270 (139)	388 (191)	0.13
Unknown	3	0	1	2	
Post-op transfusion					
	1 (2.1%)	0 (0%)	1 (3.3%)	0 (0%)	>0.9
Unknown	4	0	0	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Pre-op Hb (g/dL)					
	133 (15)	133 (14)	133 (16)	131 (14)	>0.9
Unknown	4	0	0	4	
Post-op Hb (g/dL)					
	109 (16)	108 (12)	109 (19)	110 (17)	>0.9
Unknown	6	1	1	4	
Change in Hb (g/dL)					
	-24 (10)	-24 (10)	-24 (10)	-20 (9)	0.4
Unknown	6	1	1	4	
On-Table Blood Loss					
	304 (161)	298 (137)	267 (154)	388 (191)	0.12
Unknown	3	0	1	2	
Post-op transfusion					
	1 (2.1%)	0 (0%)	1 (4.3%)	0 (0%)	>0.9
Unknown	4	0	0	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR PBA level

	Overall, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Pre-op Hb (g/dL)					
	133 (16)	133 (18)	130 (13)	135 (17)	0.7
Post-op Hb (g/dL)					
	109 (17)	110 (16)	104 (14)	113 (19)	0.3
Unknown	2	0	1	1	
Change in Hb (g/dL)					
	-24 (10)	-22 (9)	-27 (12)	-21 (8)	0.4
Unknown	2	0	1	1	
On-Table Blood Loss					
	293 (156)	320 (186)	300 (153)	276 (156)	0.9
Unknown	3	0	0	3	
Post-op transfusion					
	1 (2.4%)	0 (0%)	1 (5.9%)	0 (0%)	0.5

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

E.23 Study B: Length of stay, re-admissions, and re-operations

Relation to StR PGY

	Overall, N = 52[1]	**1/2**, N = 9[1]	**3/4**, N = 30[1]	**5/6**, N = 13[1]	**p-value**[2]
Length of Stay (days)					
	3.19 (2.41)	4.11 (3.82)	2.97 (1.92)	3.00 (2.24)	0.9
Unknown	4	0	0	4	
Re-admission to Hospital within 30days					
	1 (2.1%)	1 (11%)	0 (0%)	0 (0%)	0.11
Unknown	4	0	0	4	
Re-operation within 30days					
NO	48 (100%)	9 (100%)	30 (100%)	9 (100%)	
Unknown	4	0	0	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR STS-THR performed

	Overall, N = 52[1]	**0-19**, N = 16[1]	**20-39**, N = 23[1]	**>40**, N = 13[1]	**p-value**[2]
Length of Stay (days)					
	3.19 (2.41)	3.31 (3.07)	3.17 (2.04)	3.00 (2.24)	0.9
Unknown	4	0	0	4	
Re-admission to Hospital within 30days					
	1 (2.1%)	1 (6.2%)	0 (0%)	0 (0%)	0.4
Unknown	4	0	0	4	
Re-operation within 30days					
NO	48 (100%)	16 (100%)	23 (100%)	9 (100%)	
Unknown	4	0	0	4	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test

Relation to StR PBA level

——	**Overall**, N = 42[1]	**2**, N = 6[1]	**3**, N = 17[1]	**4**, N = 19[1]	**p-value**[2]
Length of Stay (days)					
	3.05 (2.14)	3.33 (3.01)	3.24 (2.31)	2.79 (1.75)	>0.9
Re-admission to Hospital within 30days					
	1 (2.4%)	1 (17%)	0 (0%)	0 (0%)	**0.046**
Re-operation within 30days					
NO	42 (100%)	6 (100%)	17 (100%)	19 (100%)	

[1] Mean (SD)

[2] Kruskal-Wallis rank sum test