Hip Replacement: landmark surgery in modern medical history

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Abstract

Total hip replacement (THR) is most often performed to treat end-stage symptomatic osteoarthritis. Patients typically present with increasing pain, restricted mobility and stiffness. In this procedure, the femoral head and part of the femoral neck are excised. The acetabulum is enlarged and an acetabular cup is inserted. The femoral head is replaced by a femoral component, the stem of which is inserted into the medullary canal of the femur. The components can be either cemented in place or press-fit (cementless). The THR concept was popularised by Sir John Charnley in the 1960's and although, over half a century of development has resulted in incremental improvements, the procedure is not dramatically different from the one he described. However, over the last two decades there have been significant changes in the types of bearing surfaces used. Metal on polyethylene continues to be the workhorse for the majority of cases. In the young and active, bearing surfaces with low wear rate are increasingly used. Since the early 1960s, THR has played an important role in alleviating pain and restoring mobility to millions of people. The cost-effectiveness of THR in treating advanced osteoarthritis makes it one of the most successful of all surgical interventions.

Keywords

Total Hip Replacement, Osteoarthritis, Hip Replacement

1. Introduction

The hip joint is a synovial ball and socket joint where stability is provided by the close-fit of the spherical femoral head with the cup-shaped acetabulum. The joint's stability is further enhanced by the joint capsule and ligaments which are reinforced by large muscle groups[1]. The hip joint supports a load exceeding three times body weight during level walking[2].

Total hip replacement (THR) is most often carried out to treat symptomatic end-stage primary osteoarthritis. Other indications include osteonecrosis (2%), femoral neck fracture (2%) and developmental dysplasia of the hip (2%)[3]. Rheumatoid arthritis, which formed a significant proportion of the early series of THR, now accounts for less than 1%[4] This is due to the remarkable success of medical treatments for rheumatoid disease.

The aim of this review is to discuss the role of THR in the management of hip pathology and in particular osteoarthritis. Included are summaries of the procedure, the different types of THR and outcomes associated with this surgery. In addition, the early development of THR and future perspectives are briefly discussed.

2. Osteoarthritis

Joint pathology, consistent with osteoarthritis, has been identified in Saxon[5], Medieval[5] and Roman[6] populations found on archaeological excavations in Britain. Osteoarthritis (OA) is not a single disease or process, but rather the clinical and pathological outcome of a range of disorders characterised by structural, and eventually symptomatic, failure of one or more synovial joints[7]. It is estimated that as many as 40% of people aged 65 and over have symptomatic OA of the knee or hip[8, 9].

Pain is the predominant symptom of OA. The progression of pain within OA of the hip is variable; patients often describe pain that varies over time rather than a continuous deterioration [1, 10]. The advanced stage of OA is characterised by severe pain that disrupts sleep. Ambulation becomes markedly diminished, and the use of analgesics is increased. Individuals will have limitations that impair their

ability to perform activities of daily living (ADLs), such as walking, bathing, dressing, use of the toilet, and performing house-hold chores[11]. On radiographs, the joint space is obliterated, with sclerosis, osteophytes and subchondral cyst formation[1]. The most common sites of pain are the groin, the anterior and lateral thigh, the buttock and the knee [12]. Occasionally, knee pain predominates, and misdiagnosis and investigation of the knee may delay diagnosis and treatment.

Although the causes of OA are not completely understood, biomechanical stresses affecting the articular cartilage and subchondral bone, biochemical changes in the articular cartilage and synovial membrane, and genetic factors are all important in its pathogenesis[11].

More than 50 modalities of non-pharmacological, pharmacological and surgical therapy for knee and hip OA are described in the medical literature[13]. Surgical interventions that are alternatives to THR include administration of intra-articular steroid and local anaesthetic, soft tissue releases, acetabular/femoral osteotomy, arthrodesis and arthroscopy. The aim of these procedures is to relieve pain and delay or halt further degenerative changes, negating the need for THR or delaying the age at which there is no other option[12].

3. Total Hip Replacement

3.1 Development

The development of THR is seen as a landmark in twentieth-century surgery. Philip Wiles of the Middlesex Hospital in London is credited with developing and carrying out the first THR in 1938 [14]. In the period between 1920 and 1950 Wiles was one of a number of people, in Europe and the US, contributing to the gradual evolution in surgical procedure and implant design of THR. During this period, materials that varied from stainless steel and cobalt-chrome alloys to rubber, glass, plastic and even ivory were all trialled by different groups[15]. The use of polymethyl methacrylate bone cement for fixation of total hip prostheses was popularised by Charnley in the late 1950s. The work carried out in the UK by Charnley and colleagues is responsible for much of our understanding of modern THR. They revolutionised management of the arthritic hip with the introduction of “low friction arthroplasty” using high-density polyethylene as a bearing material[16]. While early metal-on-metal hip replacements

showed promising early results[17], they were ultimately abandoned in the 1970's due to the popularity of Charnley's design. THR is a now very common procedure; in 2011 in England and Wales, 71,672 primary hip replacement procedures were carried out[4].

3.2 THR Types and Procedure

Many designs of THR prosthesis exist on the market, with every manufacturer marketing different versions of popular designs. Despite this variety, the surgical procedure varies little. The femoral neck is resected just below the femoral head, and the acetabular cartilage is removed using sequential reaming. The medullary canal of the femur is prepared using broaches, and the femoral stem and acetabular 'cup' are inserted.

The aim of the surgeon during THR is to restore, as best as possible, the pre-disease anatomy in order to restore the pre-disease biomechanics. If successful, this results in improved abductor muscle strength, a greater range of movement (ROM) and a reduced risk of post-operative complications such as limp, dislocation and wear-related implant failure[18]. Important factors include the restoration of pre-disease leg length and offset (Figure 1), and recreation of normal orientation of the femoral stem and cup (inclination and version, Figure 1). Length and offset are normally estimated by comparison with the other hip (this can be challenging if the other hip is osteoarthritic or dysplastic), with the use of templates on pre-operative radiographs, and by estimation of the tension of the peri-articular tissues intra-operatively. Whilst early designs of THR were 'monobloc', with a one-piece femoral stem and head, modern designs are modular, with a range of heads which can be attached once the stem has been inserted, which facilitates fine adjustment of leg length and offset.

Inclination and version vary between patients, and a balance must be struck between restoring the patient's native anatomy and creating a stable articulation; in practice, inclination and version are defined using a combination of patient anatomy and accepted 'normal' values. Lewinnek *et al.* identified from radiological measurements a 'safe zone' of $40^\circ (\pm 10^\circ)$ inclination and $15^\circ (\pm 10^\circ)$ ante-version to minimise the risk of dislocation (Figure 2) [19], and these values are still widely used.

Two main decisions have to be made when selecting a THR: fixation type (cemented or cementless) and bearing surface (metal, polyethylene or ceramic). Both decisions are dependent on a combination of surgeon preference and patient factors, such as age and activity level. Cemented THRs can be considered to be direct descendents of Charnley's low-friction arthroplasty (Figure 3). For the first forty years of THR, cemented fixation was almost universal. In 2005, 54% of THRs in England and Wales were cemented, and the popularity of cement has continued to decline; in 2011, only 36% of THR were cemented. In cemented THR, the femoral stem is cemented into the intramedullary canal. The acetabulum can be monobloc or modular. When monobloc, it is typically made out of polyethylene; this is also cemented into place[20]. When modular, it has a metal backing and a bearing surface of surgeon's choice, either high density polyethylene or ceramic (Figure 4). Although cemented fixation includes bone-cement and cement-implant interfaces, the bone-cement surface is the one that provides the foundation for durable fixation. Cemented THR is highly technique-dependent because the surgeon prepares the bone-cement-implant composite during the surgery[16].

In cementless THR, the components are partially or completely coated with a porous surface, which is placed directly against bone (Figure 5). The component is at first held rigidly to the bone by "press fit" with or without augmentation from screws. In the early period after the surgery, bone or fibrous tissue (or both) grows into the pores of the component's surface, providing fixation[20]. This is called primary fixation. The mechanical stability achieved after the bone surrounding the implant has adapted, is described as secondary fixation and is dependent on the success of osseointegration, i.e. the attachment of bone to implants without intervening fibrous tissue.

Cementless THRs generally have broader femoral components than cemented THRs, to facilitate the initial press-fit. Cementless acetabular components consist of a porous-coated metal 'shell' with an insert that can be polyethylene, metal or ceramic. Whilst National Joint Registries (NJR) demonstrate significantly higher rates of revision surgery for cementless THRs when compared to cemented designs, they have increased in popularity and now account for 41% of all THRs implanted[4]. There are several reasons for this: cementless THRs allow a greater choice of bearing surface and they have a shorter operative time. Theoretically, cementless fixation should be more resilient than cement, and there is

some evidence that the use of cement may be associated with a higher rate of complications and deaths, although this is very hard to demonstrate with any certainty[21]. In around 17% of cases, a hybrid THR is performed with a cemented femur and a cementless acetabulum, or vice versa[4].

The second main choice concerns bearing surface. The original Charnley hip used a metal ball and a polyethylene cup, and this remains the most popular bearing combination. However, polyethylene wear is a significant problem in younger, more active patients, and the increasing number of patients in this group receiving THR has led to an increase in popularity of harder-wearing bearing surfaces. The two main hard bearings are ceramic on ceramic and metal on metal. Ceramic/ceramic hips are becoming increasingly popular and have good longer term results; the use of metal on metal THRs has collapsed over the last five years due to the significant problems encountered with such bearings. Newer types of harder-wearing polyethylene have demonstrated good results and are increasing in popularity, used with either metal or ceramic femoral heads.

3.3 Metal-on-Metal Hip Replacement

Metal-on-metal (MoM) hip replacement became very popular in the middle part of the last decade. It promised to be a low-wearing bearing surface, with the added distinction of allowing hip resurfacing, where, rather than cutting the femoral neck and inserting a stem into the femur, the femoral head is resurfaced with a metal cap. Metal-on-metal hip resurfacing arthroplasty (MoMHRA) promised improved mechanical performance, less bone resection and, if necessary, easier revision surgery.

However, whilst there is evidence that MoMHRA works well in young active men[22], the failure rates of MoMHA in women and of metal-on-metal THR in both sexes are significantly higher than expected. Average failure rates at seven years are 11.8% for MoMHRA and 13.6% for metal-on-metal THR, although failure rates vary with the brand used (one brand of MoMTHR was reported to have a failure rate of 22% at five years[4]). This compares with rates of 3.3%-4.9% for hip implants made of other materials[23]. This high failure rate appears to be due to the pro-inflammatory effects of submicron wear particles; the effects of long-term exposure to these particles is largely unknown. In addition to the high failure rate, the mode of failure is a major concern. These failures typically involve soft tissue

and bone disruption which can be massive, leading to severe functional impairment and extremely challenging revision surgery [24-26]. These reactions have been referred to by a number of terms such as adverse reaction to metal debris (ARMD[27]), aseptic lymphocytic vasculitis associated lesions (ALVAL[28]), adverse local tissue reaction (ALTR[29]) and pseudotumour[25]

3.4 Results of THR

Implant survivorship is currently 90-95% to 10 years and around 85% to 20 years[12]. Following THR, significant improvements in both joint-specific score measurements (Oxford Hip Score) (Figure 6) and more general measures of well-being (Health-Related Quality of Life) have been demonstrated[12]. Assessment of patient and implant outcomes is necessary to identify which implant designs or surgical techniques provide the best patient benefit[3]. A variety of patient and surgical factors have been linked to a risk of various postoperative complications following THR. Patient factors influencing an increased rate of dislocation, bearing fracture, and increased wear included body mass index (BMI), age, gender, and primary diagnosis for the THR. Surgical factors influencing these risks include surgeon experience, surgical approach, prosthetic components, acetabular cup fixation method, and orientation of the acetabular cup[30]. NJRs have revolutionised the assessment of patient outcomes, implant survivorship, and surgical techniques[3].

3.3 Modes of Failure of THR

There are various ways that a THR may fail. They can become infected, they may be subject to aseptic loosening, they may dislocate, or a periprosthetic fracture may occur[12]. There is also a 40% increased risk of complications for every decade above the age of 65 years[31].

Aseptic loosening is the most common mode of failure for THR. Aseptic loosening typically occurs at the cement bone interface in hips where a MoP bearing has been used[12]. However, cementless MoP THRs, and those with other bearing surfaces, are not immune to this mode of failure[16] and there are some suggestions that cementless THR may be more susceptible to aseptic loosening[32]. The articulation of a cobalt-chrome femoral head with a polyethylene cup generates wear particles of

polyethylene with a diameter of 0.3-10 μm . The immune response to these particles causes the resorption of bone around prostheses which leads to loosening. This process has been termed osteolysis

Failure of primary THR results in the need for revision THR. Revision surgery is costlier to the health provider, the operations are time-consuming, they require an extended hospital stay and implant costs are higher. In addition, the rates of infection, dislocation and mortality are all higher with revision surgery[12].

Revision THR is performed less commonly than primary procedures. Ten percent of THRs carried out in the UK are revisions, and of these, 55% are due to aseptic loosening[4]. It has been demonstrated in Sweden that the establishment of a NJR in 1979 drove down the revision burden over subsequent decades; revision burden in Sweden is 6.4% compared with 16.9% in the US where there is no registry[33]. The effectiveness of the surgical technique was the most important factor in reducing the risk of revision due to aseptic loosening, but choice of implant was also important[34].

5. Future of Hip Replacement

In the US, between the years 1997 and 2004, there was a change in age distribution among patients receiving joint replacement. Approximately 26.5% of the primary hip surgeries performed in 1997 were on patients aged between 45 and 65 compared with 36% in 2004[35]. These trends continue today. Younger patients are demanding more of their joint replacement with longevity being amongst the most desirable features. Developments in THR have been directed at reducing the rate of failure while accommodating the high-activity profile and increased longevity of the modern patient. Components must, therefore, provide durable fixation in the face of high stresses, whereas bearing surfaces need to be resilient and show low wear[16]. Enormous efforts have been devoted to the development of new materials, designs or techniques during the last 10-15 years, in the hope of improving the endurance of the Charnley concept [36]. For example, recently, attempts have been made to further improve the wear properties of polyethylene by adding vitamin E during the production process[37].

In THR, the biomechanical situation is complicated as joint parameters including the joint centre, neck angle, and the range of motion until impingement are influenced by the operation. Furthermore, the positioning of the components in the pelvis and the femur influences the local loading situation; a slightly superior, posterior, and medial hip joint centre after replacement can be associated with markedly higher joint forces[38]. However, a THR system, which has been optimised to take these issues into account requires an accuracy of positioning and assembly which cannot be routinely achieved, even by an experienced surgeon[38]. In a growing number of operating theatres around the world, orthopaedic surgeons are being assisted by computers and computer-enabled technologies. The partnerships of human and machine benefits patients by increasing the accuracy of surgical execution and by increasing the surgically relevant information available to the physician before, during and after surgery[39].

6. Conclusions

Total hip replacement is very successful operation improving the mobility of millions of patients around the world every year. Data from national joint registries would suggest that the average age of patients having THRs is decreasing. The concomitant increase in life expectancy in the developed world means that, although good functionality is achieved with current THR technology to 20 years, the quest for wear resistance and implant longevity will go on.

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Figures

Figure 1. Synthetic anteroposterior X-ray showing the femoral offset (FO) measured in preoperative planning

Figure 2. Synthetic X-rays demonstrating the orientation of the acetabular component, anteversion angle: (A) 5° and (B) 25° and inclination/abduction angle (C) 35° and (D) 55°. Cups implanted at orientations between these angles of anteversion and inclination are less likely to be susceptible to dislocation

Figure 3. Cemented total hip replacement with modular femoral and acetabular components and a metal on polyethylene bearing (Corin)

Figure 4. Modular acetabular cups with ceramic (pink) or polyethylene bearing surfaces (Corin)

Figure 5. Cementless total hip replacement with modular femoral and acetabular components. Both components have a porous coating to allow fixation to bone. The bearing of this design is ceramic on ceramic (Corin)

Figure 6. Oxford Hip Score change following THR (NJR, 2011)

References

1. Steinberg, M.E. and L.J. Day, *The hip and its disorders* 1991, London: Saunders.
2. Bergmann, G., G. Deuretzbacher, M. Heller, F. Graichen, A. Rohlmann, J. Strauss, and G.N. Duda, *Hip contact forces and gait patterns from routine activities*. Journal of Biomechanics, 2001. **34**(7): p. 859-871.
3. Pivec, R., A.J. Johnson, S.C. Mears, and M.A. Mont, *Hip arthroplasty*. The Lancet. **380**(9855): p. 1768-1777.
4. NJR, *National Joint Registry England and Wales 9th Annual Report*, 2012.
5. Rogers, J., I. Watt, and P. Dieppe, *Medical History: Arthritis in Saxon and mediaeval skeletons*. BMJ, 1981. **283**(6307): p. 1668-1670.
6. Thould, A.K. and B.T. Thould, *Arthritis in Roman Britain*. BMJ, 1983. **287**(6409): p. 1909-1911.
7. Nuki, G., *Osteoarthritis: a problem of joint failure*. Zeitschrift für Rheumatologie, 1999. **58**(3): p. 142-147.
8. Dawson, J., L. Linsell, K. Zondervan, P. Rose, T. Randall, A. Carr, and R. Fitzpatrick, *Epidemiology of hip and knee pain and its impact on overall health status in older adults*. Rheumatology, 2004. **43**(4): p. 497-504.
9. Mannoni, A., M.P. Briganti, M. Di Bari, L. Ferrucci, S. Costanzo, U. Serni, G. Masotti, and N. Marchionni, *Epidemiological profile of symptomatic osteoarthritis in older adults: a population based study in Dicomano, Italy*. Annals of the Rheumatic Diseases, 2003. **62**(6): p. 576-578.
10. Byers, P.D., Contepom, Ca, and T.A. Farkas, *A post-mortem study of hip joint. Including prevalence of features of right side*. Annals of the Rheumatic Diseases, 1970. **29**(1): p. 15-&.
11. *Recommendations for the medical management of osteoarthritis of the hip and knee: 2000 update*. Arthritis & Rheumatism, 2000. **43**(9): p. 1905-1915.
12. Bulstrode, C., J. Wilson-MacDonald, D.M. Eastwood, J. McMaster, J. Fairbank, P.J. Singh, S. Bawa, P.D. Gikas, T. Bunker, and G. Giddins, *Oxford textbook of trauma and orthopaedics* 2011: OUP Oxford.
13. Zhang, W., R.W. Moskowitz, G. Nuki, S. Abramson, R.D. Altman, N. Arden, S. Bierma-Zeinstra, K.D. Brandt, P. Croft, M. Doherty, M. Dougados, M. Hochberg, D.J. Hunter, K. Kwoh, L.S. Lohmander, and P. Tugwell, *OARSI recommendations for the management of hip and knee osteoarthritis, Part I: Critical appraisal of existing treatment guidelines and systematic review of current research evidence*. Osteoarthritis and Cartilage, 2007. **15**(9): p. 981-1000.
14. Wiles, P., *The surgery of the osteoarthritic hip*. The British journal of surgery, 1958. **45**(193): p. 488-497.
15. Gomez, P.F. and J.A. Morcuende, *Early attempts at hip arthroplasty--1700s to 1950s*. The Iowa orthopaedic journal, 2005. **25**: p. 25-29.
16. Learmonth, I.D., C. Young, and C. Rorabeck, *The operation of the century: total hip replacement*. The Lancet, 2007. **370**(9597): p. 1508-1519.
17. McKee, G.K. and J. Watson-Farrar, *Replacement of arthritic hips by the mckee-farrar prosthesis*. Journal of Bone & Joint Surgery, British Volume, 1966. **48-B**(2): p. 245-259.
18. Grammatopoulos, G., H. Pandit, S. Glyn-Jones, P. McLardy-Smith, R. Gundle, D. Whitwell, H.S. Gill, and D.W. Murray, *Optimal acetabular orientation for hip resurfacing*. Journal of Bone & Joint Surgery, British Volume, 2010. **92-B**(8): p. 1072-1078.
19. Lewinnek, G.E., J.L. Lewis, R. Tarr, C.L. Compere, and J.R. Zimmerman, *Dislocations after total hip-replacement arthroplasties*. Journal of Bone and Joint Surgery-American Volume, 1978. **60**(2): p. 217-220.
20. Harris, W.H. and C.B. Sledge, *Total hip and total knee replacement .1*. New England Journal of Medicine, 1990. **323**(11): p. 725-731.
21. McMinn, D.J.W., K.I.E. Snell, J. Daniel, R.B.C. Treacy, P.B. Pynsent, and R.D. Riley, *Mortality and implant revision rates of hip arthroplasty in patients with osteoarthritis: registry based cohort study*. BMJ, 2012. **344**.

22. Daniel, J., P.B. Pynsent, and D.J.W. McMinn, *Metal-on-metal resurfacing of the hip in patients under the age of 55 years with osteoarthritis*. Journal of Bone & Joint Surgery, British Volume, 2004. **86-B**(2): p. 177-184.
23. Cohen, D., *Revision rates for metal on metal hip joints are double that of other materials*. BMJ, 2011. **343**.
24. Hart, A.J., S. Sabah, J. Henckel, A. Lewis, J. Cobb, B. Sampson, A. Mitchell, and J.A. Skinner, *The painful metal-on-metal hip resurfacing*. Journal of Bone and Joint Surgery-British Volume, 2009. **91B**(6): p. 738-744.
25. Pandit, H., S. Glyn-Jones, P. McLardy-Smith, R. Gundle, D. Whitwell, C.L.M. Gibbons, S. Ostlere, N. Athanasou, H.S. Gill, and D.W. Murray, *Pseudotumours associated with metal-on-metal hip resurfacings*. J Bone Joint Surg Br, 2008. **90-B**(7): p. 847-851.
26. Grammatopolous, G., H. Pandit, Y.-M. Kwon, R. Gundle, P. McLardy-Smith, D.J. Beard, D.W. Murray, and H.S. Gill, *Hip resurfacings revised for inflammatory pseudotumour have a poor outcome*. J Bone Joint Surg Br, 2009. **91-B**(8): p. 1019-1024.
27. Langton, D.J., S.S. Jameson, T.J. Joyce, N.J. Hallab, S. Natu, and A.V.F. Nargol, *Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement*. Journal of Bone & Joint Surgery, British Volume, 2010. **92-B**(1): p. 38-46.
28. Willert, H.-G., G.H. Buchhorn, I. Dipl, A. Fayyazi, R. Flury, M. Windler, G. Köster, and C.H. Lohmann, *Metal-on-metal bearings and hypersensitivity in patients with artificial hip joints. A clinical and histomorphological study*. The Journal of Bone & Joint Surgery, 2005. **87**(1): p. 28-36.
29. Schmalzried, T.P., *Metal-metal bearing surfaces in hip arthroplasty*. Orthopedics, 2009. **32**(9).
30. Callanan, M., B. Jarrett, C. Bragdon, D. Zurakowski, H. Rubash, A. Freiberg, and H. Malchau, *The John Charnley Award: Risk factors for cup malpositioning: quality improvement through a joint registry at a tertiary hospital*. Clinical Orthopaedics and Related Research®, 2011. **469**(2): p. 319-329.
31. Keener, J.D., J.J. Callaghan, D.D. Goetz, D.R. Pederson, P.M. Sullivan, and R.C. Johnston, *Twenty-five-year results after charnley total hip arthroplasty in patients less than fifty years old a concise follow-up of a previous report**. The Journal of Bone & Joint Surgery, 2003. **85**(6): p. 1066-1072.
32. Garellick, G., J. Kärrholm, C. Rogmark, and P. Herberts, *Swedish Hip Arthroplasty Register: Annual Report 2008*. Department of Orthopaedics, Sahlgrenska University Hospital, 2009.
33. Kurtz, S., F. Mowat, K. Ong, N. Chan, E. Lau, and M. Halpern, *Prevalence of primary and revision total hip and knee arthroplasty in the united states from 1990 through 2002*. The Journal of Bone & Joint Surgery, 2005. **87**(7): p. 1487-1497.
34. Herberts, P. and H. Malchau, *Long-term registration has improved the quality of hip replacement: A review of the Swedish THR Register comparing 160,000 cases*. Acta Orthopaedica, 2000. **71**(2): p. 111-121.
35. Kim, S., *Changes in surgical loads and economic burden of hip and knee replacements in the US: 1997–2004*. Arthritis Care & Research, 2008. **59**(4): p. 481-488.
36. Huiskes, R., *Failed innovation in total hip-replacement - diagnosis and proposals for a cure*. Acta Orthopaedica Scandinavica, 1993. **64**(6): p. 699-716.
37. Oral, E., K.K. Wannomae, S.L. Rowell, and O.K. Muratoglu, *Diffusion of vitamin E in ultra-high molecular weight polyethylene*. Biomaterials, 2007. **28**(35): p. 5225-5237.
38. Knahr, K., *Tribology in total hip arthroplasty* 2011: Springer.
39. DiGioia, A.M., B. Jaramaz, F. Picard, and L.-P. Nolte, *Computer and Robotic Assisted Hip and Knee Surgery* 2004: Oxford University Press, USA.