Epidemiology of Long-Term Health Outcomes and the Response of Knee Cartilage to Bowling Biomechanics in Elite Cricketers

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Doctor of Philosophy

Mary Elizabeth "Betsy" Jones

Oriel College

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Abstract

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Doctor of Philosophy in Musculoskeletal Sciences

Mary Elizabeth "Betsy" Jones, Oriel College, Michaelmas 2017

Background: Sport is an important form of physical activity and has been shown to have many health benefits. Cricket is a popular sport in the UK and internationally, but little is known about the short- and long-term health effects of a career in elite cricket. This thesis will describe the long-term physical and mental health of former elite cricketers compared to the general population, explore the association of cricket-related factors with their long-term musculoskeletal health, and evaluate the effect of elite fast bowling on the knee cartilage of current elite fast bowlers.

Methods: A sample of male former elite English cricketers was recruited for a cross-sectional retrospective questionnaire study of the long-term health of former cricketers. Chronic conditions in the former cricketers were compared to a general population sample and cricket-related factors including playing position and injury were tested for their association with musculoskeletal outcomes. A sample of male and female current elite fast bowlers was recruited for a biomechanics and cross-sectional MRI study of their knee cartilage. The knee cartilage was compared between the bowlers' trailing leg versus the higher loaded leading leg, and was tested for associations with bowling kinematic and kinetic parameters.

Results: The former elite cricketers reported a higher prevalence of osteoarthritis, total hip replacement, total knee replacement, anxiety and depression than the general population sample and a lower prevalence of heart problems than the general population. Injury was the only cricket-related factor analysed to be associated with the musculoskeletal outcomes of joint pain, osteoarthritis, and joint replacement in the former cricketers. The current elite fast bowlers did not demonstrate a statistically significant difference between the compartmental knee cartilage volume in the trailing leg versus the higher loaded leading leg. A clinically significantly greater cartilage volume was found in the lateral tibia compartment of the leading leg than the trailing leg. The lateral tibia cartilage of the leading leg was also found to be significantly associated with the knee flexion/extension moment and abduction/adduction moment at leading leg strike of the bowling action.

Conclusions: This research identifies risks and benefits of a career in elite cricket, providing targets for prevention and resource provision for chronic conditions in current cricketers and cricketers transitioning out of elite cricket. These results also suggest that cartilage may be sensitive to bowling loads in current elite fast bowlers, providing evidence that increased physical activity and loading is associated with increased cartilage volume.

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Abbreviations

3T	3.0-Tesla
ACLR	Anterior cruciate ligament reconstruction
ACR	American College of Rheumatism
ADL	Activity of Daily Living
BMI	Body Mass Index
BW	Body Weight
CHD	Chronic heart disease
CI	Confidence Interval
COM	Centre of mass
CRN	Clinical Research Network
CVD	Cardiovascular disease
DESS	Dual-echo in steady state (MRI)
DZ	Dizygotic (twins)
ECB	England and Wales Cricket Board
ELSA	English Longitudinal Study of Ageing
EPV	Events per predictor
FIESTA-C	Fast imaging employing steady-state acquisition (phase cycling) (MRI)
G&S	Grood and Suntay convention
GEE	General Estimating Equations
GP	General Practitioner
GP-OA	GP-diagnosed Osteoarthritis
GRF	Ground Reaction Force
HSE	Health Survey for England

ICC	Intra-Class Correlation Coefficient
IRAS	Integrated Research Application System
JCS	Joint Coordinate System
K/L	Kellgren/Lawrence scale
KOOS	Knee injury and Osteoarthritis Outcome Score
MCID	Minimal clinically important difference
MOST	Multicenter Osteoarthritis Study
MRI	Magnetic resonance imaging
MSK	Musculoskeletal
MZ	Monozygotic (twins)
NCSEM	National Centre for Sport and Exercise Medicine
NHANES	National Health and Nutrition Examination Survey
NRES	National Research Ethics Service
OA	Osteoarthritis
OR	Odds Ratio
PCA	Professional Cricketers' Association
PIG	Plug-In Gait
PPI	Patient and public involvement
QOL	Quality of life
R&D	Research and Development
REC	Research Ethics Committee
REDCap	Research Electronic Data Capture system
RMSCoV	Root-Mean-Square Coefficient of Variation

SD	Standard Deviation
SMR	Standardised morbidity (mortality) ratio
SPGR	Spoiled gradient recalled echo acquisition in the steady state (MRI)
SSFP	Steady-state free precession (MRI)
SSI	Site-Specific Information
TE	Excitation time (MRI)
THR	Total hip replacement
TJR	Total joint replacement
TKR	Total knee replacement
TR	Relaxation time (MRI)
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

Chapter 1 Introduction

1.1 Rationale

Sport as a form of physical activity has been shown to have many benefits for physical and mental health. However, some evidence suggests that elite sport can have deleterious effects on musculoskeletal health. Cricket is one of the world's most popular sports, with adult participation estimated at 844,000 players in England and Wales alone (1). Nevertheless, little is known about the long-term effects of elite cricket on the health of former elite cricketers or the short-term effects of elite cricket on joint mechanics of current elite cricketers. This thesis aims to describe the short- and long-term associations of cricket with chronic conditions, including musculoskeletal health, and to investigate the underlying mechanisms for musculoskeletal health in samples of former and current elite cricketers.

Sports governing bodies and player associations have called for research to understand the burden of diseases in their sports, as well as the role of sport in developing chronic conditions. The England and Wales Cricket Board (ECB) and the Professional Cricketers' Association (PCA) recognised the increased risk factors to which elite cricketers are exposed, and have collaborated to achieve the aims of this thesis. Further, all those involved in this research recognise that understanding the benefits and potential negative consequences of elite cricket will help to inform healthy participation in this popular sport.

While little is known of the long-term health of former elite cricketers, some studies of other former elite athletes have found increased rates of osteoarthritis (OA) compared to inactive participants (2). OA is a degenerative joint disease that can cause significant

pain, making it a leading cause of disability (3). Current literature does not provide strong evidence to support an increased relationship with elite sport participation and OA; however, some evidence suggests that sport injury and increased loading in elite sport play a significant role (2). Understanding sport-specific factors that are associated with OA may help in OA prevention in an elite athlete population. Elite cricket is a unique sport in which to address this question because of the nature of game at the elite level. Elite cricketers may have to play for 5 consecutive days, which requires physical and mental endurance from players and exposes them to developing gradual onset injuries. The cricket literature, however, does not address how these factors associate with long-term musculoskeletal health in former players. Gouttebarge *et al* recognised the need for studies to address these questions in order to identify those at risk for early onset OA and to provide them with resources to preserve their health and functioning in their post-sport life (4).

Beyond describing the long-term musculoskeletal health of cricketers, the cricket literature has also yet to investigate the short-term effects of elite cricket and potential mechanisms for OA in cricketers. Fast bowlers in particular are strategically critical in a cricket team and their bowling action causes their lower limbs to experience the greatest loading of any other cricket playing position (5). However, little is understood about how, or if, the lower limbs of fast bowlers respond to this loading. Understanding this question may inform OA prevention for fast bowlers and contribute to the understanding of how cartilage responds to load.

This thesis will use samples of current and former elite cricketers to investigate short- and long-term health effects of elite cricket. Study of the former elite cricketers will contribute to the understanding of health benefits and risks in elite cricket. This research will also evaluate the knee cartilage volume and biomechanics of current elite fast

bowlers in order to better understand the sensitivity of cartilage to loading and a potential mechanism for OA in these players.

1.2 Aim

The aim of this thesis is to describe the long-term health of former elite English cricketers.

1.3 Objectives

1. To define and compare the rates of chronic conditions in a sample of former elite cricketers to those of a general population sample.
2. To define the prevalence of joint pain, OA, and joint replacement in a sample of former elite cricketers, and to explore the association of injury and cricket-related factors with these outcomes.
3. To assess the effect of elite fast bowling loads on knee cartilage volume in the leading versus trailing legs, as a potential mechanism for OA.
4. To test the sensitivity of cartilage to loading conditions by evaluating the associations of kinematic and kinetic parameters during the bowling action with knee cartilage volume.

Chapter 2 Literature Review

This chapter will review the literature addressing the benefits and risks of physical activity and sport, the epidemiology of osteoarthritis (OA) in general and elite athlete populations, and mechanisms for OA with respect to cartilage and gait mechanics. In each of these areas, cricket will be discussed as a sport model.

2.1 Physical Activity and Long-Term Health

Physical activity is suggested to be a critical component in primary prevention and treatment of many of the most common chronic conditions, both physical and mental illnesses (6,7). This section will describe the benefits and risks of physical activity for physical and mental health and wellbeing.

2.1.1 Physical Activity, Sport Participation, and Physical Health

Leading causes of death or disability include the chronic conditions of heart disease, diabetes, and OA. Physical activity has been shown to prevent or mitigate the effects of these conditions (8). A common concern around physical activity is its effect on joint health and risk of OA. Many studies have shown that physical activity does not increase risk of OA when done regularly and at a moderate level, and may even decrease the risk of developing severe OA that leads to joint replacement (9–12).

2.1.1.1 Osteoarthritis and Elite Sport

Unlike regular, moderate activity, physical activity performed at a high level or intensity has been associated with increased risk of OA. Some studies suggest that OA is more common in certain former elite athletes, such as footballers (2,4). Studies of former elite athletes have a high risk of selection bias, as athletes with OA are more likely to participate in the study, and OA is not consistently defined across studies, but existing

research suggests that elite athletes in certain sports are at a higher risk of OA. One study of the relationship between OA and common mental disorders in former elite athletes collected cross-sectional self-reported OA in 27 South African former elite cricketers aged 50 or younger; however, the prevalence of OA in the cricketers was not reported (13). Therefore, no known studies have reported on the prevalence of OA in former elite cricketers.

Physical activity has been shown to have major benefits in both primary and secondary prevention of many chronic conditions that are leading causes of death and disability, such as chronic heart disease and diabetes (8,14). For chronic heart disease and diabetes, benefits can be seen across all ages, even among adults that start an exercise regimen late in life (8). Physical activity, especially sport and recreational activities, has been consistently associated with decreased incidence of hypertension, coronary heart disease, stroke and other cardiovascular outcomes (8,15–18). A study of former Finnish elite athletes found team and endurance sport athletes to have significantly decreased mortality due to heart disease and stroke compared to controls (19). No known studies have addressed these conditions in former elite cricketers.

Physical activity has also been shown to be beneficial against incidence of dementia and Alzheimer's disease. Research suggests an inverse relationship between regular physical activity in midlife and older age and incidence of dementia and Alzheimer's disease in healthy adults (20–22). Former elite power sport athletes in Finland have been shown to have an increased risk of mortality due to dementia compared to controls, while no significant risk was found for endurance or team sport athletes (19). No known studies have described dementia prevalence in former elite cricketers.

2.1.2 Physical Activity, Sport Participation, and Mental Health and Mental Illness

Mental illnesses have been associated with increased all-cause mortality and can decrease an individual's likelihood of accessing medical care for chronic conditions (23). These factors support including mental illness as an important indicator of overall health. In this discussion, a distinction is made between mental health and mental illness. The World Health Organization (WHO) defines mental health in a positive perspective, emphasizing that mental health requires more than the absence of mental illness (24). Further, the psychology literature references the Keyes two continuum model, in which the presence of mental illness, such as diagnosed anxiety or depression, does not imply the absence of mental health, and vice versa (25).

The NHS pathway to care for mental illness includes the option for organised physical activity (26). Physical activity has been shown to be associated with positive effects for mental health both in the general population, and in elite athletes (27–31). In a general population sample, sport in particular showed a beneficial, inverse dose-response effect for symptoms of mental illnesses (27).

Elite athletes have been shown to have comparable rates of mental health conditions as the general population. Studies of current elite German, French, and Australian athletes have found rates of mental illness to be comparable to those of the general population of each nation (29–31). A systematic review of mental illness in elite athletes noted that these athletes experience unique stressors that may make them vulnerable to mental illness. However, the results demonstrated that elite athletes have comparable rates of mental illness as the general population (32). One study of current professional cricketers in South Africa found a prevalence of symptoms of anxiety and depression in 37% of the current players, comparable to that of the South African population (33).

The vast majority of literature reviewed addressed current elite athletes; however, depression and anxiety occurs for many athletes during their transition out of elite sport (34). Capturing the mental health of elite athletes during or after this transition phase was rare. However, the study of South African current cricketers also recruited a sample of former professional cricketers. Of these former cricketers, 24% reported symptoms of anxiety and depression (33). The previous cricketer study did not report physician-diagnosed mental illness, and recognised that cultural differences would be expected to impact the generalizability of results to former professional cricketers of different nations.

As previously mentioned, mental health is considered distinct from mental illness. Some studies suggest that elite athletes may experience above-average mental health, or flourishing, which would not be captured in a clinical diagnosis (35). A positive mental health effect from a career in elite sport may be suggested in how former elite athletes reflect on their career. The retired elite athlete literature reviewed has not addressed such a career reflection measure as an indicator for mental health and wellbeing.

While physical activity and sport participation have demonstrated physical and mental health benefits, no studies have assessed all of these outcomes in former professional cricketers.

2.2 Osteoarthritis

The previous section described the physical and mental health benefits of physical activity and identified OA as a potential risk of elite physical activity or sport. OA is a degenerative joint disease affecting cartilage and many surrounding tissues and is suggested to be more prevalent in former elite athletes (2,3). This section will describe

the epidemiology of OA, how it is captured in epidemiological studies, and its risk factors, particularly in elite athletes.

2.2.1 Burden of Osteoarthritis

OA is the most common form of arthritis, affecting an estimated 27 million people in the US in 2005 and an estimated 8.75 million people in the UK in 2013 (36,37). OA can result in loss of hyaline articular cartilage, abnormal subchondral bone remodelling and attrition, osteophytes, periarticular muscle weakness, and in some cases ligamentous laxity and synovial inflammation (38). These changes in and around an osteoarthritic joint can also lead to serious functional limitations and disability (3,36,39). Such functional limitations and disability contribute to the large indirect economic and societal costs of OA, including lost wages, lost productivity, early retirement and disability pensions (40,41). The direct medical costs are also substantial, including pain medication, GP and rheumatology clinic visits, physiotherapy, and joint replacement surgery (40,41). These costs are expected to rise as rates of knee pain and symptomatic knee OA are increasing (42).

2.2.2 Defining Osteoarthritis

OA has both structural and symptomatic components, and can be defined clinically, radiographically, symptomatically, or by self-report. Clinically defined OA is characterised on the basis of symptoms and physical examination findings. Radiographic OA is typically determined from evaluation of radiographs of a joint using the Kellgren/Lawrence (K/L) graded scale, which assesses structural signs of OA. OA is usually defined as grade II or higher on the K/L scale. Symptomatic OA is characterised by both radiographic evidence and frequent pain in a joint (36). Self-reported OA requires a patient to report their diagnosis or symptoms, and can identify OA using parts or combinations of the other OA definitions described. The prevalence of OA

depends upon the definition used. For example, OA prevalence increases if only radiographic OA is considered, compared to symptomatic OA (3).

2.2.2.1 Self-reported Osteoarthritis

Self-reported OA is an important metric, as it can capture the epidemiology of a disease without the time and resources required for the use of radiographs or a physical exam. As with all self-reported conditions, it can be biased if participants are unsure of their diagnosis or if they under- or over-estimate their symptoms, but it remains an effective tool for epidemiological research. A variety of tools have been developed to capture self-reported OA.

Self-reported pain questions are one method of capturing OA-related pain. Several such instruments exist, such as the National Health and Nutrition Examination Survey (NHANES) joint pain questions, the Western Ontario and McMaster Universities OA (WOMAC) index, and the joint-specific Knee injury and Osteoarthritis Outcome Score (KOOS). While WOMAC and KOOS are validated, useful indices for pain and function, with KOOS tailored for evaluating the knee, NHANES pain questions are often used for self-reported OA-related pain in population cohort studies (43). NHANES is a cross-sectional survey that assesses "nationally representative samples of the noninstitutionalized US population", including questions for self-reported OA (42). The literature shows the evolution of NHANES question wording, leading to an NHANES-type question that was adopted as the American College of Rheumatism (ACR) criteria for knee osteoarthritis: Have you had knee pain on most days of the last month? (44). This NHANES-type question, or NHANES pain, was also used as the gold standard NHANES wording by an expert consensus meeting (45). Because NHANES pain is common in large cohort studies of OA, such as Chingford and the Multicenter Osteoarthritis Study (MOST), it is useful for the direct comparison of OA prevalence between these populations.

Self-reported physician-diagnosed OA, or self-reported GP-OA, ("Have you ever been told by a doctor that you have arthritis?") is another self-report metric. Self-reported GP-OA was compared with self-reported arthritis ("Do you have arthritis or rheumatism?") and self-perceived arthritis ("Do you have arthritis or rheumatism? Please [indicate] the joints where you have arthritis pain") and validated against radiographs. The correlation (Cohen's kappa) of self-reported GP-OA and radiographic OA was 0.64, showing self-reported GP-OA to be the most predictive of radiographic OA compared to self-reported and self-perceived arthritis (46).

Finally, self-reported joint replacement surgery, or total joint replacement (TJR), has also been used to identify OA in epidemiological studies. Self-reported TJR has been shown to have a high specificity for OA in an NHANES study, meaning that TJR is a good tool for identifying patients with OA (47,48).

In cross-sectional studies, self-reported TJR would be expected to capture end-stage OA, while NHANES pain or GP-OA would be expected to capture early or moderate OA. Therefore, the best estimate of OA prevalence in a population, using self-report measures, would include all three of self-reported NHANES pain, GP-OA, and TJR. However, the existing studies of former elite athletes have not included all of these self-report measures to estimate the prevalence of OA.

2.2.3 Risk factors for Osteoarthritis

While OA is most visibly identified by structural changes to the joint, the current conceptual model describes OA "as a whole-person disease", with risk factors originating from more than the joint alone. Both systemic and mechanical factors contribute to the "susceptibility of joints to damage and failure of repair" (49).

Non-modifiable risk factors for OA include age, sex, and family history of OA (50). OA prevalence is strongly associated with increasing age across a variety of joints (51). OA

prevalence studies have shown females to have higher rates of OA than males, and for obesity to be more strongly associated with OA in females than males (52,53). A family history of OA, or genetic factors, has also been shown to explain 50% or more of all OA (54).

Modifiable risk factors for OA include occupation, body mass index (BMI), and joint injury (50). Occupational joint loading, particularly occupations requiring repeated or sustained kneeling, squatting, heavy lifting or standing, has been shown to be strongly associated with increased OA prevalence (55,56). BMI has been consistently shown to be strongly positively associated with increased incidence, prevalence and progression of OA (57,58). Finally, joint injury has been repeatedly shown to be strongly correlated with increased OA prevalence and incidence (57,59,60). Joint injury can lead to joint instability, joint malalignment, or decreased proprioception. These changes to the joint after injury can lead to altered mechanics and increased joint loads that contribute to OA (60).

Other risk factors, including ethnicity (48,61), smoking status (62), hormone replacement therapy (63), and type of physical activity or sport (12), also have evidence of associations with increased OA prevalence. The modifiable and non-modifiable risk factors described here are important as potential confounders when analysing OA in a population sample.

2.2.3.1 Osteoarthritis, Elite Sport, and Injury

As previously mentioned, joint injury is a known risk factor for OA and studies of former elite athletes from various sports have suggested a higher prevalence of both lower and upper limb OA in former elite athletes compared to the general population or to other occupations (4). One hypothesis for the apparent increased risk of OA in elite athletes is the increased risk of injury (10,60,64–66). The risk of OA has been found to

increase in men that "practice injury-prone types of sport" greater than 3232 hours over their lifetime (67).

A number of studies have addressed the association of injury history with subsequent OA in former elite athletes, and all of the known studies investigating this relationship have identified a significant association between injury history and OA (2,4,68–70). A study of former elite Australian Football League athletes found that half of its respondents suffered with arthritis, and 57% of those with arthritis suffered from OA associated with a previous serious lower limb injury (70). Multiple studies of former elite footballers have found significant association between knee injury and subsequent knee OA (2). Kujala et al found a significant association between injury history and radiographic knee OA in former elite Finnish athletes (69).

2.2.3.2 Injury in Elite Cricket

Various injury surveillance studies have been performed for current elite and professional cricketers, detailing injury rates that would warrant further investigation of long-term effects. A study of elite New Zealand cricket found an injury prevalence of 10.2% over 6 seasons (71). A longitudinal study of South African national and provincial cricketers over 3 seasons found an average of 1.9 injuries per player per season; 22.2% of the recorded injuries were joint injuries (72). A 15-year prospective study of 235 first class Australian fast bowlers reported 4.8 injuries per 100 player innings, or about 2.4 injuries per 100 overs. The greatest risk factors for joint injury in the prospective study of Australian fast bowlers were a high career workload (≥3000 match overs) and a high workload in the previous season (≥450 overs) (73).

Some aspects of cricket, particularly at the elite level, contribute to an increased injury risk. The lack of a truly structured calendar at the international level means that elite cricketers have a varied number of matches of varied lengths each year. Cricket does not allow for substitute bowlers, which usually results in the remaining bowlers

unexpectedly increasing their workload if a bowler on their team becomes injured (73). As mentioned in Chapter 1, some forms of cricket matches also require a great amount of physical and mental endurance from the players, who may play for 5 consecutive days. For these reasons, cricket presents as an excellent sport model for gradual onset injuries.

OA is an increasingly prevalent and costly disease suggested to be more prevalent in former elite athletes; however, no studies have investigated the prevalence of OA and the association of injury history with OA in former elite cricketers.

2.3 Cartilage

One hypothesis for the apparent increased risk of OA in former elite athletes is increased joint loading, leading to faster cartilage degradation than recreational or moderate activity (10,60,64–66). For example, a study of former Australian Football League athletes showed playing load to be positively correlated with OA later in life (70). Studies of the response of cartilage to loading, however, suggest that the type of loading is key in understanding how cartilage responds.

Articular cartilage has a small proportion of chondrocytes, the living cells, and is mostly an extracellular tissue consisting primarily of water, type II collagen, and proteoglycans with glycosaminoglycan (GAG) side-chains (74). Mow et al described cartilage as biphasic, consisting of the solid matrix phase, or collagen and proteoglycans, and the interstitial fluid phase (75). Mow et al demonstrated that under constant, sustained loading, or stress relaxation testing, and under constant, sustained strain, or creep testing, cartilage is best modelled as viscoelastic because it exhibits both elastic and viscous behaviour (75). GAG side-chains are negatively charged and attract cations and water, causing swelling of the proteoglycans and increased tension in the extracellular matrix of cartilage. Under impact loading, cartilage responds as an elastic material

because the fluid is unable to dissipate. Under more sustained loading, cartilage responds as viscoelastic because the fluid has time to dissipate and demonstrate the viscous behaviour of the biphasic material (76). During dynamic loading, water will dissipate under compression, and the negatively charged GAG side-chains will attract the water back into the cartilage as compression is reduced. More GAG side-chains lead to increased tension, allowing healthy cartilage to withstand tension and shear forces and providing the mechanical properties for cartilage to resist compression under static and dynamic loads (77).

2.3.1 Cartilage Response to Load *In Vitro*

In vitro studies of articular cartilage have described the mechanisms that adapt cartilage to mechanical load (77). Healthy cartilage has been shown to respond positively to dynamic, cyclic compression by increasing production of proteoglycans and GAGs and increasing proliferation of chondrocytes (78–80). However, cartilage can respond negatively to injurious loading. Injurious loading can be static or dynamic loading with excessive force outside physiological ranges, or can be loading within normal physiological ranges but on damaged or abnormally structured cartilage (81). Injurious loading can disrupt catabolic and anabolic activity, which can deplete extracellular matrix components and damage the mechanical properties of the cartilage (81). *In vitro* studies of cartilage demonstrate that healthy cartilage proliferates under dynamic, cyclic loading within physiological ranges, and that cartilage can be depleted under injurious loading.

2.3.2 Cartilage Response to Load *In Vivo*

2.3.2.1 Loading in Elite Athletes versus Controls

Consistent with *in vitro* studies of articular cartilage, *in vivo* studies suggest that some loading involved in sport may lead to healthy adaptation in cartilage. Previous studies,

shown in Table 2.1, have predominantly shown that certain elite athletes demonstrate an increase in knee cartilage thickness compared to inactive controls, though conflicting evidence exists (82–85).

Table 2.1. Summary of relevant published literature assessing cartilage thickness in athletes.

Authors	Subjects	Sports	Outcome
Gratzke *et al* (2007)	28 males (14 control, 7 weight lifters, 7 bobsled sprinters)	Weight lifters, bobsled sprinters	Weight lifters & bobsled sprinters had significantly thicker patellar cartilage than nonathletic controls
Muhlbauer *et al* (2000)	18 (9 male triathletes, 9 inactive males)	Triathletes	No statistically significant differences; however, triathletes had thicker cartilage in the patella, femoral trochlea, and lateral femoral condyle. Triathletes had statistically insignificantly thinner cartilage in the medial femoral condyle, and medial and lateral tibial plateau
Grzelak *et al* (2014)	33 (13 elite male weight lifters, 20 age & BMI matched controls)	Weight lifters	Weight lifters had increased cartilage thickness in weight bearing and non-weight bearing regions of knee joint
Eckstein *et al* (2002)	36 (9 male triathletes, 9 female triathletes, 18 inactive controls)	Triathletes	No statistically significant differences in cartilage thickness, but triathletes had significantly larger knee joint surfaces

2.3.2.2 Healthy Loading *In Vivo*

Other studies have used cartilage morphology metrics to capture the response of cartilage to different types of load and at different stages of the life course. While decreased mechanical stimulation, such as after surgical intervention in one leg or in paraplegic patients, has been consistently shown to result in cartilage thinning (86,87), healthy, increased loading has been shown to correlate with cartilage accrual. A longitudinal MRI study of community-based adolescent children aged 9-18 years suggested that cartilage volume accrual was greater in children undertaking more vigorous physical activity (88). In adult females, GAG content was estimated using delayed Gadolinium Enhanced Magnetic Resonance Imaging of Cartilage (dGEMRIC); a 10-week Start To Run program demonstrated that GAG content increased in the knees of asymptomatic, untrained female novice runners compared to sedentary controls (89). Consistent with healthy loading of cartilage *in vitro,* these studies demonstrate the

adaptive response of healthy *in vivo* articular cartilage to load within normal physiological ranges.

2.3.2.3 Loading During Normal Gait: Kinematics

Previous studies have shown certain cartilage metrics to be associated with kinematic parameters of normal gait. The flexion/extension angle of the knee at heel-strike of walking has been shown to correlate with the location of greatest knee cartilage thickness (90,91). The more extended the knee flexion angle was at heel-strike of walking, the further anterior was the location of the thickest medial femoral cartilage. Koo et al and Scanlan et al developed cartilage thickness maps for the femoral cartilage using high contrast MRI. While the approach to cartilage thickness mapping was different in each of these studies and the locations of thickest cartilage had large variation between participants, the locations of thickest cartilage in the medial femoral condyle were associated with knee flexion angle at heel-strike in both studies (90,91). Both Koo et al and Scanlan et al base their analyses on the assumption that knee flexion at heel-strike is a surrogate for anterior-posterior contact location of femoral cartilage. However, this limited analysis to the knee flexion angle and sagittal plane. Kinematic relationships in other planes were not addressed, though this was recommended by the authors.

2.3.2.4 Injurious Loading *In Vivo*

As found in the *in vitro* studies, injurious loading of cartilage *in vivo* does not tend to yield a null or positively adaptive response. Excessive loading of healthy cartilage can result in microstructural alterations; if this loading is sustained, it may be linked to early cartilage degeneration. This was shown in a pilot study of elite American college football linemen, who experience a great deal of loading in training and competition. Players that had multiple seasons of play at the collegiate level had decreased GAG content, measured using dGEMRIC, compared with players with only one season at the

collegiate level (92). This study is one example of excessive cartilage loading through sport and the negative response of cartilage.

2.3.2.5 Injurious Loading During Normal Gait: Kinematics and Kinetics

Loading within normal physiological ranges, such as normal gait, but on damaged cartilage can also be injurious loading. Osteoarthritic cartilage, at various stages of the disease, can be characterised by fissures, erosion, and denudation, all of which reflect the depletion of extracellular matrix components (93). This structural disruption affects the mechanical properties of the cartilage, which affects its response to load. Andriacchi and colleagues suggest that a kinematic change during walking can shift load to regions of cartilage that are not conditioned for that load (94). If these regions are osteoarthritic, or begin to degrade, this change in load distribution can cause a negative response in the cartilage and increase the rate of progression of OA (94). This has been demonstrated in osteoarthritic patients, where an increased load due to altered gait kinematics was associated with more rapid OA progression (95).

Kinetic parameters during gait have also been associated with worsening OA. A larger knee adduction moment can increase the medial force experienced by the knee (96). Several studies have demonstrated an increased knee adduction moment to be positively associated with worsening pain and poorer clinical outcomes in knee OA patients (94,97,98,96,99). Increased knee flexion moment has also been identified as a predictor of OA progression (94,96,100). Most of these studies have used MRI to determine cartilage thickness, though these calculations have improved with advancing MRI machines and analysis techniques. Two of these studies found increased knee adduction moment and knee flexion moment to be associated with decreased tibial cartilage thickness (96,100). Chehab et al found these results after 5-year follow-up, while Erhart-Hledik et al conducted a cross-sectional study of seventy OA patients. The gait parameters identified

in these studies cause abnormally large loads on diseased cartilage, contributing to the increased progression of OA in the lower limbs.

2.3.3 Genetic Component of Cartilage Morphology

Though both *in vitro* and *in vivo* evidence exists to support the ability of cartilage to adapt to load, evidence also exists to suggest that these adaptations are largely due to genomic factors. Antoniades and colleagues investigated the minimum joint space width in the hip of 222 monozygotic (MZ) and 240 dizygotic (DZ) twins, finding that genetic factors explained the majority of variation in hip joint space width (101). A second twin study, conducted by Hunter and colleagues, investigated the knee cartilage volume of 31 MZ and 37 DZ twin pairs, finding that between 61 - 76% of knee cartilage volume could be explained by genetic factors, depending on the knee compartment (102). A third, smaller study of 12 MZ twin pairs found a coefficient of variance of 3.2% for knee cartilage thickness in the twins, compared to 12 and 11% in a reference population of young women and men, respectively (103). Eckstein *et al* investigated the cartilage morphology of the functionally dominant and non-dominant lower limbs in fifteen healthy volunteers; the within-person comparison allowed for control of genetic factors. While muscle cross sectional area differed in the thigh, no statistically significant difference between the cartilage volume, cartilage thickness, or joint surface area was found between the functionally dominant and non-dominant knees (104).

The studies mentioned support the hypothesis that cartilage thickness and volume depend on genomic factors, rather than a response to mechanical exposures. This is the view summarised in a review by Eckstein and colleagues, who suggest that cartilage did not evolve to respond to mechanical loading like bone and muscle due to a lack of evolutionary pressure. However, the twin studies cited in support of this hypothesis do not report on the mechanical loading differential within twin pairs. Further,

environmental factors, especially in adolescence, have been shown to impact joint morphology (105). These twin studies acknowledge that environmental factors during development are expected to be the same within twin pairs. These studies are cross-sectional, with data collected in adulthood and without differing environmental factors during development. They do not allow for the testing of the response of cartilage to certain environmental factors, such as physical activity, while controlling for genetic factors.

None of the reviewed literature described a study in which the effect of loading on cartilage morphology was tested while controlling for genetic factors.

2.3.4 Cartilage Metrics

In order to measure the effect of any exposure on cartilage morphology, cartilage volume and thickness are often reported metrics for cartilage morphology (11). The methods for measuring cartilage thickness can be inconsistent, with studies reporting local or regional thickness, and maximum, minimum, or average cartilage thickness in a region of interest. The main limitation of cartilage volume is that it can be a difficult metric to compare between persons due to the effect of bone surface area (106). This limitation can be overcome by normalising cartilage volume by bone surface area, making cartilage volume a more comparable, consistent metric for cartilage morphology than cartilage thickness.

2.3.5 Cricket Fast Bowling as a Sport Model

Current elite cricketers present a valuable model for assessing the response of cartilage to load. A key aspect of an elite game of cricket is fast bowling, which delivers the cricket ball to a batsman. Fast bowling is performed by cricketers referred to as “fast bowlers” and is a full body action. The motions most unique to fast bowling occur during the delivery stride (5). The delivery stride starts at trailing foot strike, includes the

subsequent leading foot strike, and ends with ball release. Studies of the ground reaction forces (GRF) during trailing foot and leading foot strike have demonstrated the force differential between the two legs. Among studies of fast bowlers, peak vertical GRF in the trailing foot ranged from 2.37 – 2.9 times body weight (BW) while the peak vertical GRF in the leading foot ranged from 5.75 – 6.4 BW. The peak braking, or horizontal, GRF ranged from 0.94 - 1.1 BW in the trailing foot and from 1.9 – 3.54 BW in the leading foot (5,107,108). Fast bowling is a repetitive action, and the force differentials are experienced during every bowl. Therefore, fast bowling at an elite level may cause differing cartilage adaptation in the leading and trailing legs.

Though Eckstein and colleagues (104) found no difference in cartilage thickness or volume between the dominant and non-dominant knees of healthy adults, the force differential experienced by each leg in a sample of healthy participants is unlikely to be as significant as that experienced by each leg of an elite fast bowler. Hind and colleagues did not find bone density to be significantly different between legs at the proximal femur of elite male fast bowlers (109); however, Hind and colleagues have found increased bone density in the lumbar spine on the leading foot side of club-level, young fast bowlers in an unpublished study. Hind and colleagues did not assess bone density at or near the knee in either study. The differential seen at the lumbar spine, and lack of investigation into possible cartilage morphology differences at the knee, motivates further investigation.

No studies have yet been conducted to assess the structural adaptive response of cartilage at the knee in the leading versus the trailing leg of elite fast bowlers. Investigation of cartilage volume in the leading versus trailing legs of healthy fast bowlers would provide a unique model for a within-person case-control study of the *in vivo* response of cartilage to load, while controlling for genetic factors.

2.4 Summary

Physical activity has been shown to have a myriad of long-term health benefits but some sports at the elite level may have negative long-term consequences, such as OA. OA has been measured in several studies of former elite athletes, and also poses the largest healthcare burden among musculoskeletal conditions in former elite athletes. The response of cartilage to load throughout an athlete's life may impact their likelihood of developing OA in later life. Elite cricketers provide an excellent sport model to further investigate the association of sport and sport-specific factors with OA and other long-term conditions. Elite fast bowlers provide a unique sport model to investigate the response of cartilage to loading. The results of such investigations would have implications for future elite cricketers and for athletes in sports that have similar biomechanical movements, like baseball, tennis, and golf. Beyond athletes, the results of these investigations can improve the current understanding of the mechanisms by which OA develops, which can inform recommendations for healthy participation in sport and physical activity for the general population.

Chapter 3 Methods: Former Elite Cricketer Study

3.1 Study Design and Aims

This chapter will describe the study design and methods used for the cross-sectional retrospective questionnaire-based study in a population sample of former elite cricketers. This study addressed the first two thesis objectives:

1. To define and compare the rates of chronic conditions in a sample of former elite cricketers to those of a general population sample.
2. To define the prevalence of joint pain, osteoarthritis (OA), and joint replacement in a sample of former elite cricketers, and to explore the association of injury and cricket-related factors with these outcomes.

This chapter will describe stakeholder involvement, questionnaire development including patient and public involvement (PPI), ethics approval, recruitment and data collection, data cleaning for analyses, and statistical methods.

3.2 Stakeholder Involvement

The England and Wales Cricket Board (ECB) and the Professional Cricketers' Association (PCA) expressed interest in understanding the long-term health of former elite cricketers and the role of cricket participation in their long-term health. The PCA maintains a former player contact list, which allowed for the targeted recruitment of former elite, English cricketers.

3.3 Participants: Former Elite Cricketers

Participants were recruited from the PCA's member contact list that includes 1500 former players. Due to restricted access to the PCA contact list, an email was drafted for the PCA to send out to its members including an introduction to the study, the participant information sheet, and instruction on how to take part. A study-specific email address was generated within the University and the PCA initial contact email instructed potential participants to email the study address with their intention to participate. Email addresses could be added to the online database used for this study, the Research Electronic Data Capture (REDCap) system (110). REDCap generated questionnaire invitations in response to requests to participate. Participants were also able to request postal or telephone versions of the questionnaire through the study email address. The full recruitment strategy is shown in Figure 3.1. It is recognized that this multi-step process to recruit participants may have impacted the study recruitment, but was the only way to maintain control of the study's sample using the REDCap database and work with the restricted access to former player contact details.

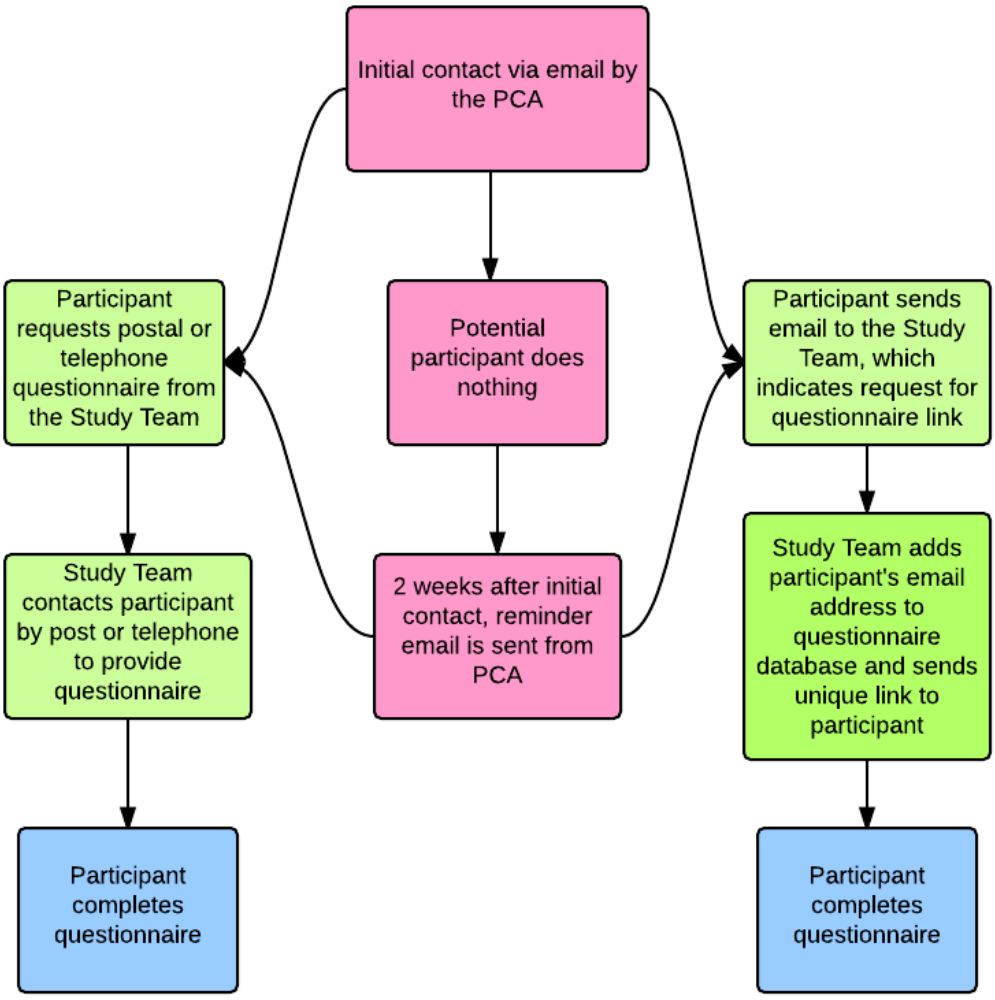


Figure 3.1. Recruitment strategy for the cross-sectional questionnaire former player study.

Recruitment lasted for four months, with one reminder email sent to the former player member list two weeks after the initial email about the study.

3.4 Ethics

The study was given favourable opinion by the National Research Ethics Service (NRES) Committee London Stanmore (REC 15/LO/1274) and adopted onto the Clinical Research Network (CRN) Portfolio, after completion of the process shown in Figure 3.2. NHS ethics approval was sought so that the questionnaire can be validated with medical notes for a random sample of participants in a later project.

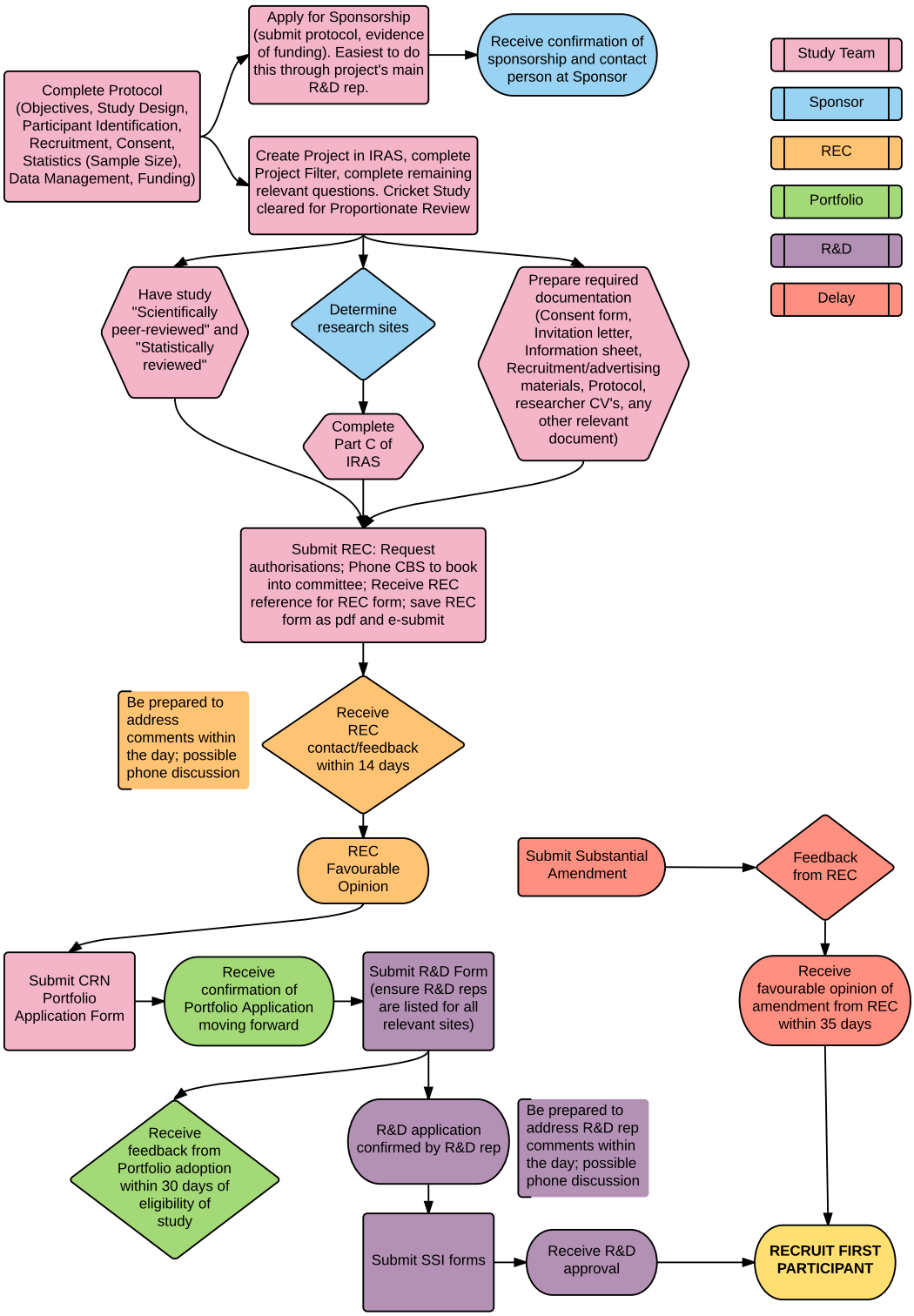


Figure 3.2. NHS Health Research Authority ethics approval flowchart. The colour-coded legend is in the top right corner. Acronyms: R&D: Research and Development; IRAS: Integrated Research Application System; REC: Research Ethics Committee; CRN: Clinical Research Network; SSI: Site-Specific Information.

3.5 Questionnaire Development

3.5.1 Rugby Study

The Rugby Study is a cross-sectional retrospective questionnaire study to address long-term health in retired elite rugby players and its questionnaire was used as a template for the current study in cricket (111). Madeline Davies at the University of Oxford led the Rugby Study as part of the Arthritis Research UK Centre of Sport, Exercise, and Osteoarthritis. The Rugby Study developed its questionnaire through extensive Patient and Public Involvement (PPI). The Rugby Study questionnaire was separated into seven sections, which have been mirrored in the current study: Personal Details, Medical History, Playing History, Current Pains, Past Injuries, Family History, and Occupation. Comparability between the responses to the rugby and the cricket study questionnaires was desired; therefore, the phrasing of as many questions and answer options as possible was maintained in the cricket version of the questionnaire. PPI was required to establish cricket-specific equivalent questions and answer options to the rugby-specific questions. Some questions were also identified as requiring PPI to determine if they were relevant to a population of former cricketers. An example of this was the concussion section in the Rugby Study questionnaire, which was not maintained in its entirety for the cricket questionnaire.

3.5.2 Patient and Public Involvement (PPI)

PPI was conducted to inform the content of the retrospective questionnaire and question phrasing, especially for cricket-specific questions, and to advise on recruitment methods. Six PPI interviews were held with a total of 12 participants; all participants had experience with cricket in some capacity at a high level of competition. At each interview the project was explained as an assessment of long-term health in former elite cricketers and the questionnaire in its preliminary state was provided to PPI participants. Topic

guides were written for each set of interviews, each slightly tailored to the participants' cricket experience; a sample topic guide can be found in the Appendix A.

Each PPI interview consisted of participants grouped by their connection to cricket. The 4 current players were all male, consisting of 3 fast bowler-batsmen and a medium-fast bowler-batsman from the Oxford University Cricket Club. The 3 former players were all male except for one female; most former players were still involved in the sport as coaches or other supporting roles. The 3 cricket physicians and physiotherapists were all male and were practicing as medical professionals for elite cricketers at the time of interview. The 2 representatives from the Professional Cricketers' Association were also both male, had personal experience in elite cricket, and worked regularly with former elite cricketers.

Participants were asked for feedback on what they thought was the purpose of the questionnaire, to which they responded generally that the questionnaire appeared to capture the medical and playing histories of cricketers. The inclusion of the Medical History section, which asks whether the respondent has ever had certain conditions diagnosed by a Doctor, caused the participants to think that the questionnaire was concerned with the overall health of cricketers, rather than only their joint health. The thorough Injury History and Current Pain sections implied to participants that joint health was a priority for the questionnaire.

Participants were asked to assess the clarity, completeness, and content of the questionnaire overall and for specific questions of interest. The cricket-specific questions inspired several suggestions to improve clarity of the questions and completeness of answer options. For example, both retired cricketers and current Oxford University Blues cricketers clarified the answer options for levels of play for a UK-based population.

Participants did not find any questions to be uncomfortable to answer; questions regarding medical history were perceived to be appropriate given the context of the questionnaire relating to a medical purpose. The participants did feel, however, that the questions regarding concussion were not suited to a cricketer population. The concussion section, therefore, was reduced from the version included in the Rugby Study in order to provide more relevant responses for cricket.

PPI participants also felt that the best recruitment method was via email. A paper, postal questionnaire was identified as the second preferred method.

3.5.3 Questionnaire Translation: Paper to Online

The questionnaire went through multiple iterations to translate from the paper questionnaire used in PPI to an online format on the REDCap system (110). The REDCap version allowed for mutually exclusive answer options, "select all that apply" answer options, as well as nested questions. The control of answer types ensured that conflicting responses could not be selected, where appropriate. Nested questions meant that some questions only appeared if a certain response to a previous question had been selected. This was meant to improve the experience of the participant, as only questions relevant to the answers they provided would appear.

The paper version was maintained and used as a postal option for participants that did not prefer to complete the questionnaire online or by telephone. The paper questionnaire is included in Appendix B.

3.6 Data Cleaning and Variable Generation: Former Cricketers

Questionnaire response data was extracted from the REDCap questionnaire database. REDCap exported a Stata file that labelled all variables and values in the dataset. The accuracy of this file was tested by tabulating randomly selected variables and checking

whether the tabulated responses matched expected or reasonable responses. This file was then used for data cleaning and variable generation.

3.6.1 Demographic Variables

3.6.1.1 Age

Age was calculated as the participant's year of birth subtracted from 2016, the year by which all participants completed the questionnaire. It is recognized that this may overestimate the age of some participants. One-hundred and ninety participants reported an age variable. The youngest participant was 28; the oldest participant was 88.

3.6.1.2 Body Mass Index (BMI)

BMI was calculated as a participant's weight in kilograms divided by their height in meters squared. Where appropriate, units were converted to kilograms and meters before calculating BMI. Six participants entered only "pounds" and no "stones" for their weight; this was interpreted to be "pounds" as the standalone unit and converted accordingly to kilograms. There were 188 participants with a valid BMI, ranging from 21.3 to 53.1.

3.6.1.3 Ethnicity

Ethnicity was divided into white and non-white, due to the low number of minority responses. Responses of "Black", "Asian", or "Mixed" were categorized as "non-white", which accounted for up to 5% of participants. No participants reported their ethnicity to be "other".

3.6.1.4 Smoking Status

Smoking status was reported as "Yes", "No", or "Ex-smoker". These responses were categorized in the following way: a response of "no" was categorized as "Does not smoke", suggesting that the participant never smoked; a response of "Ex-smoker" was categorized as "Ex-smoker"; and a response of "yes" was categorized as a "Current smoker".

3.6.2 Cricket-related Variables

Cricket-related variables of cricket-related injury, playing position, time since retirement, playing load, and functionally dominant side were generated.

3.6.2.1 Cricket-related injury

Only severe injuries were recorded in this study. A severe injury was defined as an injury leading to more than 4 weeks of reduced participation in exercise, training or sport. Severe injuries were recorded for the spine, shoulder, elbow, finger/hand, wrist, hip/groin, knee, and ankle. A cricket-related injury was defined as a binary variable indicating one or more injuries incurred on a joint while training, playing, or warming up for cricket. Side-specific data for cricket-related injuries were not recorded. If a participant indicated that they had had a joint injury but did not report whether this injury was cricket-related or not, the injury was assumed to be cricket-related. It is recognized that this may overestimate the number of injuries that were cricket-related.

3.6.2.2 Playing Position

Playing position was generated from the question "Predominant playing position as a player (after age 16)". While many cricketers will have played in more than one capacity in their career, this playing position question offered eleven mutually exclusive answer options, requiring the participant to choose only one "predominant" position. The answer options were categorized into "Batsman", "Wicketkeeper", "Fast bowler", and "Spin bowler." These categories, based on grouping positions into similar biomechanical movement categories, were devised under the advisement of physicians within the ECB and are consistent with those recommended by Orchard et al for injury surveillance of cricket (112). "Wicketkeeper" included participants that selected wicketkeeper or wicketkeeper / batsman. "Fast bowler" included participants that selected medium pace, fast-medium, or fast bowler, and participants that selected all-rounder with

medium pace, fast-medium, or fast bowling. “Spin bowler” included participants that selected spin bowler or all-rounder with spin bowling.

3.6.2.3 Years Since Retirement

Years since retirement from cricket was calculated from the year of retirement subtracted from 2016, the year by which all participants completed the questionnaire.

3.6.2.4 Playing Load

Playing load was captured by the number of professional seasons. Playing load was intended to quantify load due to elite cricket, so the number of professional seasons captured the most intense period of cricket training and playing for a former elite cricketer. Number of professional seasons was defined as the sum of the reported number of professional seasons played in the UK and those played abroad. Five participants responded “don’t know” to the number of professional seasons played abroad and were assigned a value of zero seasons abroad. It is recognised that this treatment of “don’t know” responses may have underestimated the playing load of these five participants. Alternative variables to capture playing load were number of seasons at the highest level and number of seasons at the level played for the majority of the cricket career. Number of seasons at the highest level was not used because it risked underestimating the elite level load of players that may have played at the international level for one or two seasons, but at the First Class County level for several seasons. Number of seasons at the level played for the majority of the cricket career was not used because it risked overestimating the elite level load of players that played for a First Class County for one or two seasons, but played tens of seasons at a recreational level.

3.6.2.5 Functionally Dominant Side

Functionally dominant side was only used in a subanalysis in bowlers. Functionally dominant side for bowlers was defined on the basis of functional load during bowling. The “dominant” side was defined as the lower limb side expected to see the greatest ground reaction force while bowling and the “non-dominant” side was the lower limb

side expected to see the lesser ground reaction force while bowling. This meant that the "dominant" lower limb was their leading leg when bowling and the "non-dominant" lower limb was their trailing leg. For example, right-handed bowlers had a "dominant" left leg and a "non-dominant" right leg.

3.6.3 Outcome Variables: Former Elite Cricketer Long-Term General Health

3.6.3.1 Chronic Conditions

The outcome variables for the former elite cricketer chronic conditions analysis were: heart problems, high blood pressure, stroke, diabetes, asthma, OA, total hip replacement (THR), total knee replacement (TKR), anxiety, depression, and dementia. Apart from OA, THR, and TKR, these chronic conditions were presented as a list after the question "Has a doctor ever told you that you have or have had any of the following?" GP-diagnosed OA was captured with the question "Have you ever been told you have wear and tear, degeneration, or osteoarthritis by a doctor?" Joint replacement was captured with the question "Have you ever had a joint replacement?" If a participant indicated that they had a joint replacement, joint- and side-specific data was collected for their joint replacement to determine if they had a THR or TKR on either side. The answer options for each of the chronic conditions were "yes", "no", and "don't know." The response of "don't know" for any of these outcomes was coded as the participant not having the condition for the binary outcome variables. Less than 2% of participants responded "don't know" to any outcome variable. A sensitivity analysis did not find a significant difference between this treatment of "don't know" responses and treating "don't know" responses as missing.

3.6.3.2 Career Reflection

Career reflection of the former cricketers was analysed as a secondary measure of long-term health. The career reflection responses were divided into 3 categories, as indicated by the colour-coded chart in Figure 3.3, due to low numbers of responses in the yellow

and red answer options. The 3 categories were chosen as they captured similar sentiments in the response.

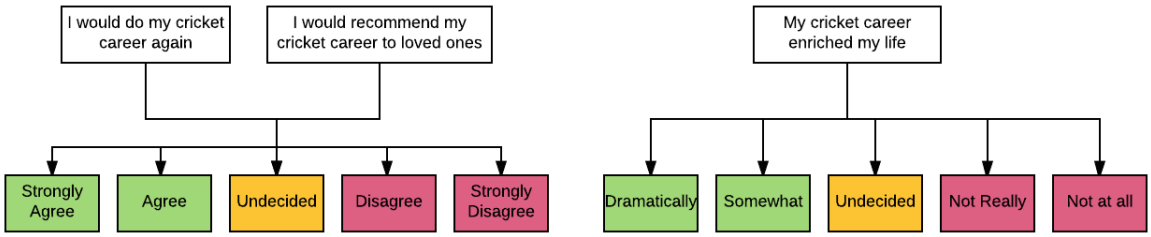


Figure 3.3. Colour-coded demonstration of the answer categorization of the career reflection questions.

3.6.4 Outcome Variables: Former Cricketer Musculoskeletal Health and Cricket-Related Risk Factors

The outcome variables of interest to evaluate the musculoskeletal health of the former cricketers were: NHANES pain, GP-diagnosed OA, and joint replacement. All of the outcomes had answer options of "yes", "no", and "don't know" for each joint. Responses of "don't know" were coded as the participant not having the condition for the binary outcome. "Don't knows" accounted for less than 1% of any of these outcomes. Binary variables were generated for each joint site of NHANES pain, GP-diagnosed OA, and joint replacement. Side-specific variables for each outcome at each joint site were also generated.

3.6.4.1 NHANES Pain

NHANES pain was defined as pain in a joint on most days of the last month. NHANES was not used in the chronic conditions analysis due a lack of data in the comparator population.

3.6.4.2 GP-diagnosed OA

GP-diagnosed OA was defined as in Section 3.6.3.1. If a participant indicated that they had OA, joint- and side-specific data were collected for their OA. From exploring the

data for GP-diagnosed OA, a number of participants had specified their back or neck within "Other joint." Therefore, a variable was created for the joint site "spine or neck".

3.6.4.3 Joint Replacement

Joint replacement was defined as in Section 3.6.3.1 for joint- and side-specific joint replacements. Three participants indicated that they had a joint replacement but did not indicate that they had GP-diagnosed OA. As joint replacement was used as a measure of OA in this study, the responses of these three participants were further explored. Of the three participants, two were determined to have had a joint replacement for causes other than OA and were excluded from analysis. Based on the injury history of the third participant, it was reasonable to assume their joint replacement was treatment for post-traumatic OA and they were retained in analyses.

3.6.4.4 Poor Joint Outcome

One variable was created in order to capture a more clinically relevant joint outcome in the analysis of long-term musculoskeletal health and cricket-related risk factors. Poor joint outcome was defined as a positive response to any of NHANES pain, GP-OA, or joint replacement at a joint. This was done to increase the power of results when assessing cricket-related risk factors and to provide a single, synthesized outcome to indicate joint trouble for a participant. It is recognized that this variable does not necessarily indicate that a participant currently has trouble in a joint. However, it does indicate that at some point in the participant's life, they experienced long-term pain, had a diagnosis of OA, or had a joint replacement in that joint.

3.7 Data Cleaning and Variable Generation: Comparator Population

For the former elite cricketer chronic conditions analysis, it was necessary to have a comparator population in order to give context to the prevalence of chronic conditions in

the former cricketers. The general population sample for this analysis was from the English Longitudinal Study of Ageing (ELSA).

3.7.1 Comparator Population: English Longitudinal Study of Ageing (ELSA)

ELSA is a longitudinal survey of representative households in England. ELSA participants were recruited from households that responded to the Health Survey for England (HSE) in 1998, 1999, and 2001. Wave 0 of ELSA includes some demographics from these initial HSE responses. Eligible participants for ELSA were aged 50 and above or were a partner living with the sample member at the time of the HSE who was not age-eligible, or who had joined the household since the HSE interview (113). Computer aided personal interviewing (CAPI) was used to administer the core ELSA questionnaire between 2002 and 2003. This fieldwork period collected Wave 1 data for the study, consisting of 12,099 responses (113). Demographic data variables were retrieved from Wave 0 of ELSA, when these variables were not collected at Wave 1. The average time between Wave 0 and Wave 1 was determined to be approximately 4 years. A weighted average of the years that participants' data were collected for Wave 0 was determined to be early 1999. The year of Wave 1 data collection was not reported, so this was estimated to be early 2003. These estimates produced the average estimated time between Wave 0 and Wave 1 data collection of 4 years.

Wave 0 and Wave 1 ELSA core questionnaire data were requested from and provided by the UK Data Service. The UK Data Service's variable and question bank was used to identify the variable names needed for this analysis.

ELSA consisted of 5335 men; these men had an average age of 64.4 years (standard deviation (SD) 10.3 years) and a BMI of 27.5 (SD 3.8).

3.7.2 Demographic Variables

3.7.2.1 Age and BMI

Participant age was calculated from the participant's age during Wave 1 ELSA data collection.

BMI data was not collected during Wave 1, so was taken from Wave 0 of ELSA. As mentioned, an estimated average of 4 years elapsed between Wave 0 and Wave 1 data collection. It is recognized, therefore, that BMI may have changed during this time and may not be precise.

3.7.2.2 Ethnicity

Ethnicity was extracted from Wave 0 of ELSA, as it was not collected in Wave 1. Ethnicity had already been categorized into "white" and "non-white", so this categorisation was maintained.

3.7.2.3 Smoking Status

Smoking status was extracted from Wave 1 of ELSA. Smoking status was categorized in the following way: "Does not smoke", for participants that reported having never smoked cigarettes; "Ex-smoker", for participants that reported having smoked cigarettes before, but subsequently reported that they do not smoke cigarettes nowadays; and "Current smoker", for participants that reported having smoked cigarettes before, and subsequently reported that they do smoke cigarettes nowadays.

3.7.3 Outcome Variables: Comparator Population Long-Term General Health

The same eleven chronic conditions of interest for the former cricketers were of interest in the comparator population. Six of the eleven chronic condition variables, those of heart problems, high blood pressure, stroke, diabetes, asthma, and dementia, were cleaned in a similar way. Participants were presented with a card containing a list of related chronic conditions. They were asked if they had ever been told by a doctor that they have or have had any of the conditions on the card. A participant was categorized

as having a chronic condition if they identified that condition from the card. Participants that refused to answer were categorized as missing and excluded from further analysis. For the heart problems variable, participants that indicated that they have or have had any of six heart conditions, including "any other heart trouble", were categorized as having heart problems.

To be categorized as having OA, the participant must have indicated that a doctor has told them that they have or have had arthritis. The participant was then presented with a new card listing types of arthritis; OA was defined as a response of "osteoarthritis" from this card.

Joint replacement was captured with the question "Have you ever had any joint replacements?" ELSA is unique for joint replacements because participants aged under 60 were not asked about joint replacement. A response of "not applicable" indicated that the participant was aged under 60 and these participants were excluded from joint replacement analysis. Hip replacement and knee replacement were derived from positive responses to any hip or knee replacement, respectively.

For all of these conditions, responses of "don't know" were coded as "no".

3.7.4 Variable Harmonization: Chronic Conditions in the Former Cricketers and Comparator Population

Variable harmonization between the former cricketers and the general population (ELSA) for each chronic condition outcome is shown in Table 3.1.

Table 3.1. Variable harmonization between the former cricketers and the normal population (ELSA) for each outcome. Answer options for the former cricketers were "yes", "no" and "don't know" for each outcome. Branching questions are indicated with instructions in italics.

Outcome	Question(s), answer(s) posed to former cricketers	Question(s), answer(s) posed to normal population (ELSA)	Harmonised Variable
Introductory question:	Have you ever been told you have any of the following by a Doctor?	Has a doctor ever told you that you [have/have had] any of the conditions on this card? What others?	
Asthma	• Asthma	• Asthma	• Asthma
Dementia	• Dementia	• Dementia, organic brain syndrome, senility, or any other serious memory impairment	• Dementia
Diabetes	• Diabetes	• Diabetes or high blood sugar	• Diabetes
High blood pressure	• High blood pressure	• High blood pressure or hypertension	• High blood pressure
Stroke	• Stroke	• A stroke (cerebral vascular disease)	• Stroke
Heart problems	• Heart problems	• Angina • A heart attack (including myocardial infarction or coronary thrombosis) • Congestive heart failure • A heart murmur • An abnormal heart rhythm • Any other heart trouble	• Heart problems: positive response to any of the six heart conditions posed to the normal population
Anxiety Depression	• Anxiety • Depression	*If answered,* "Any emotional, nervous, or psychiatric problems" *Then asked,* "What type of emotional, nervous, or psychiatric problems do/did you have?"	
		• Anxiety • Depression	• Anxiety • Depression
Osteoarthritis	Have you ever been told that you have wear and tear, degeneration, or osteoarthritis by a doctor?	*If answered,* "Arthritis (including osteoarthritis, or rheumatism)" *then asked,* "Which type or types of arthritis do you have?"	
		• Osteoarthritis	• Osteoarthritis
Hip and Knee replacement	"Have you ever had joint replacement surgery?" *If answered,* "Yes" *then asked,* "If yes, where?"	"Have you ever had any joint replacements?" *If answered,* "Yes" *then asked,* "Which joints did you have replaced?"	• THR: positive response to one or both hips, or hip(s) and knee(s)
	• Hip • Knee	• Hip • Both hips • Knee • Both knees • Hip(s) and knee(s)	• TKR: positive response to one or both knees, or hip(s) and knee(s)

3.8 Statistical Methods

This section describes the statistical methods used for the cross-sectional retrospective questionnaire study. A summary of statistical methods will also be included in relevant experimental chapters.

3.8.1 Missing versus Non-missing

For the former cricketer long-term health and musculoskeletal health objectives, t-tests and chi-squared tests were used to assess the effect of missingness. Complete case analysis was used in reported results due to low missing data. Participants excluded due to missing participant characteristics, predictors, or outcomes were compared to those included in analysis. This missing versus non-missing analysis is important in informing whether participants were not missing at random and whether excluded participants shared a distinctly different characteristic to those included in analysis, such as a higher BMI.

3.8.2 Post Hoc "Don't Know" Sensitivity Analysis

To determine how to handle responses of "don't know" within the questionnaire, post hoc sensitivity analyses compared the results of analyses after treating "don't know" responses in different ways. In one analysis "don't know" responses were treated as missing, and in a second analysis they were treated as "no". Treating "don't know" responses as "no" responses did not significantly change the result of any analysis and also improved the power of results with increased sample size. Therefore, "don't know" responses were treated as "no" for the reported analyses in this study.

3.8.3 Prevalence

The prevalences of the eleven chronic conditions, career reflection responses, and the joint- and side-specific musculoskeletal outcomes of interest for the former cricketers were calculated for this thesis. The prevalences of the eleven chronic conditions were

also calculated for the comparator population. Lifetime prevalences, or the proportion of participants that had a condition at any point in their lives, were reported for the chronic conditions. As it is defined in this study, pain was reported as period prevalence, or the proportion of participants that experienced pain within a given timeframe: "the last month". Stata 14.2 was used to calculate the prevalences and 95% confidence intervals reported in this thesis.

3.8.4 Standardised Mortality Ratios (SMRs)

Standardised Mortality Ratios (SMRs), also referred to as Standardised Morbidity Ratios, were used to compare prevalences of the eleven chronic conditions between the former cricketers and the comparator population sample, ELSA. The "study population" was the former cricketer sample and the "standard population" (also referred to as the "reference" or "normal" population) was the comparator population sample.

There are two methods of standardisation for SMRs: direct and indirect. Direct standardisation produces a "directly standardised rate", while indirect standardisation produces an "indirectly-standardised SMR" (114). The two methods of standardisation set the weights for each category, or "stratum", differently. This different weighting can cause direct standardisation to provide imprecise stratum-specific rates in the study population if the study population has small sample sizes for some strata. Indirect standardisation does not have the same issue with small strata in the study population. Therefore, indirect standardisation was used to accommodate the small sample sizes in some strata of the former cricketers.

Using indirect standardisation, the rates for each stratum in the standard population are the "observed rates." These are applied to each stratum of the study population to calculate the expected rate for each stratum. The expected rates are then summed. The

sum of observed cases for the study population are divided by the sum of expected rates (115). This is also shown in equation 3.1**:**

$$Indirectly\ standardized\ SMR = \frac{\sum cases\ in\ the\ study\ population}{\sum(R_k \times N_k)} \quad \textbf{[3.1]}$$

where:

R_k = rate for the *k*-th stratum of the standard population (ELSA)

N_k = number of persons in *k*-th stratum of the study population (cricketers)

An SMR calculated using indirect standardisation can be interpreted as how the number of observed cases in the study population compares with the expected number of cases in the study population if the study population had the same matched characteristic rates as the standard population.

Stata 14.2 and Microsoft Excel were used for standardisation and to calculate SMRs and 95% confidence intervals.

3.8.5 Sensitivity and Specificity

Sensitivity and specificity were used to evaluate the overlap in the three musculoskeletal outcomes of interest in the former cricketers: NHANES pain, GP-diagnosed OA, and joint replacement. Sensitivity measures the proportion of positives that are correctly identified as positive; specificity measures the proportion of negatives that are correctly identified as negative. As inclusion of the three musculoskeletal outcomes was intended to ensure that OA was captured at any stage of progression, the sensitivity and specificity of these outcomes indicated how the measures overlapped. Stata 14.2 was used to calculate both sensitivity and specificity.

3.8.6 Multivariable Logistic Regression

Logistic regression was used to test the association of cricket-related risk factors with binary, joint-specific poor joint outcomes (116). All of the logistic regression analyses and assumption testing for this thesis were completed using Stata 14.2. Odds ratios and 95% confidence intervals were reported.

The three assumptions of logistic regression models were tested for each model in former cricketer analyses:

1. The model is correctly specified: all relevant independent variables are included and any irrelevant independent variables are excluded (117)
2. The observations are independent and collected accurately (116)
3. The independent variables are not collinear, or are not a linear combination of other independent variables in the model (117)

3.8.6.1 Correctly Specified Models

The models in this thesis were assumed to be correctly specified. Although some covariates may not have been statistically necessary, a strong clinical motivation justified their inclusion. One example of this was the inclusion of BMI as a confounder for joint-specific OA.

3.8.6.1.1 Interaction Terms

Interaction terms were not included in the models of this thesis. Brookes et al showed through a simulation study that a study's sample size would have to be inflated by 16-fold in order to maintain the power of a result that had an interaction effect that was no less than half the size of the overall effect (118). This means that for this study, any interaction effect would have to be several times the overall effect in order to maintain the power of the result without requiring an increase in sample size.

3.8.6.2 Independent, Accurately Collected Observations

The person-level observations, such as NHANES knee pain, for this thesis are known to be independent and assumed to be collected accurately. The known limitation of this assumption is that the observations were self-reported. Side-specific observations, such as NHANES right knee pain, may not be independent. Therefore, generalized estimating equations (GEE) were used in analysis of side-specific observations. GEE is further discussed in section 3.8.7.

3.8.6.3 Collinearity

The collinearity of independent variables was tested for the variables used in this thesis. Cricket-related risk factors had collinearity between two risk factors, playing position and functionally dominant side. Functionally dominant side was generated based on playing position. However, these variables were not used in the same analysis and no other collinearity was found.

3.8.6.4 Post Hoc Linearity Testing and Summary Statistics

The estimated logistic probabilities and fractional polynomials were plotted with continuous variables for each model to test the model's linearity. To maintain linearity, participant age had to be categorized for some models. Categorisation was statistically driven by the fractional polynomial plot, with categorical boundaries selected at the point in the continuous variable that linearity was lost.

The summary statistics of Pregibon leverage, standardised Pearson residual, and deviance residual were calculated and plotted for each logistic regression model in this thesis. The logistic regression models in this thesis were intended to be descriptive, rather than predictive. Therefore, the summary statistics were calculated but not used to exclude potentially influential observations.

3.8.6.5 Events per Predictor

To maintain the stability of a model, it is common practice that logistic regression should only be used when at least 10 events per predictor (EPV) exist. Fewer than 10 EPV tends

to yield unreliable confidence interval coverage, increasing bias and variability (119). Research suggests, however, that statistically significant results with 5 – 9 EPV can still yield confidence interval coverage within acceptable levels (119). Due to the sample size of this study, the threshold for running a logistic regression model was 5 or more EPV. Models with fewer than 5 EPV were classified as unstable and results were not reported.

3.8.7 Generalized Estimating Equations (GEE)

GEE were used where the logistic regression assumption of independent observations could not be satisfied. For example, a participant may have had a serious injury to their left hip, resulting in a poor joint outcome in that hip. The injury may have altered their gait and resulted in a poor joint outcome in their right hip, even though they never experienced a right hip injury. GEE accounted for such potential "clustering" of side-specific observations within a participant. While logistic regression provided "person-level" analysis, GEE allowed for "side-level" analysis.

Stata 14.2 was used for GEE analysis with robust standard errors, an assumed binomial distribution on the outcome, and an assumed exchangeable within group correlation structure.

3.9 Summary

This chapter described the methods for the objectives regarding the prevalence of chronic conditions in former elite cricketers compared to a general population sample, and the prevalence of musculoskeletal outcomes and their association with injury and cricket-related risk factors. The methods described in this chapter addressed stakeholder involvement, questionnaire development including PPI, ethics approval, recruitment and data collection, data cleaning and variable generation, and statistical methods.

Further details, such as inclusion and exclusion criteria for each analysis, will be included in relevant methods sections of Chapters 4 and 5.

Chapter 4 Prevalence of and Risk for Osteoarthritis and Other Long-Term Health Outcomes in Former Elite Cricketers

4.1 Introduction

Limited research has investigated the long-term health of former elite athletes and no studies have been conducted in former elite cricketers with a holistic view of physical and mental health, and career reflection and wellbeing (4,120). Understanding the benefits and possible negative outcomes of elite sport participation may help in prevention and mitigation of these risks and in informed participation. The chronic conditions of heart problems, high blood pressure, stroke, diabetes, asthma, osteoarthritis (OA), total hip replacement (THR), total knee replacement (TKR), anxiety, depression, and dementia were of interest, due to the large body of research suggesting that physical activity may be an important component in their prevention (6). Career reflection was also of interest as an indication of the effect of one's career on their mental health and wellbeing.

The aim of this study is to describe the prevalence of chronic conditions and to analyse the risk for chronic conditions in former elite cricketers compared to a general population sample. The secondary aim is to describe the career reflection of these former elite cricketers. As no known data on the long-term health of cricketers existed previously, these aims were critical to first provide context to this population and their overall health. These aims were addressed for the former cricketers using the cross-sectional retrospective questionnaire described in Chapter 3. The cardiovascular, musculoskeletal and mental health outcomes in the former elite cricketers were compared with the general population using the English Longitudinal Study of Ageing (ELSA).

4.2 Methods

This study used a retrospective cross-sectional questionnaire study design. The aim of this study was approached with two analyses, which utilised different sample sizes from the former cricketer sample. First, the prevalence of chronic conditions in the former cricketers was described for the complete former cricketer sample. Second, the prevalences of chronic conditions in the former cricketers were compared to a general population sample. The methods and results sections of this chapter are structured to reflect these two analyses.

4.2.1 Prevalence of Chronic Conditions in Former Cricketers

Part one of the aim was to describe the prevalence of chronic conditions in the former cricketer population. All chronic conditions in the former cricketer population were self-reported, GP-diagnosed conditions.

4.2.1.1 Former Cricketers

As described in Chapter 3, all members of the Professional Cricketers' Association (PCA) on the PCA's "former players" membership list were invited to participate in the study. Recruitment lasted for four months; 1500 former cricketers were contacted and a response rate of 13% resulted, with 80.2% of cricketers that requested the questionnaire completing the study.

4.2.1.2 Inclusion Criteria

Male former cricketers with complete data for age, BMI, and chronic conditions were included in this analysis. Demographic variables analysed were age, BMI, smoking status, and ethnicity. The cricket-specific variables of predominant playing position and mean years since retirement were also reported.

4.2.1.3 Missing versus Non-Missing

A missing versus non-missing analysis, using chi-squared tests and t-tests, compared the characteristics of participants included in complete case analysis versus those excluded

from analysis due to missing data. Missing versus non-missing analysis evaluated how representative the sample of former cricketers included in analysis was compared to those excluded for missing data.

4.2.1.4 Prevalence

Stata 14.2 was used in this analysis. Prevalence values of heart problems, high blood pressure, stroke, diabetes, asthma, OA, THR, TKR, anxiety, depression, and dementia were calculated using complete case analysis in the former cricketer population. Percentages and 95% confidence intervals were calculated.

4.2.2 Comparison of Former Cricketer Chronic Conditions with General Population

Part two of the aim was to analyse the risk for chronic conditions in former elite cricketers compared to a general population sample. The career reflection questions were analysed as a secondary aim of this analysis.

4.2.2.1 Former Cricketers and General Population Comparator Sample

The former cricketers in this analysis were taken from the same sample described in the previous section.

As described in Chapter 3, the English Longitudinal Study of Ageing (ELSA) was used as the comparator, general population sample. Demographic variables analysed for the general population were age, BMI, smoking status, and ethnicity. These variables, as well as the eleven chronic conditions, were generated as described in Chapter 3.

4.2.2.2 Study Inclusion/Exclusion Criteria

Only male participants from the former cricketers and general population with complete data for age, BMI, and the chronic conditions analysed were included for complete case analysis. The former cricketers were standardised by age and BMI with the general population sample, so only participants aged 50 to 89 and with a BMI above 18.5 were included in matched analysis. General population participants aged under 60 were not

asked joint replacement (TJR) questions, so participants aged under 60 in both population samples were excluded in THR and TKR matched analysis.

4.2.2.3 Chronic Conditions

Chronic conditions of interest were again: heart problems, high blood pressure, stroke, diabetes, asthma, OA, THR, TKR, anxiety, depression, and dementia. These outcomes were all self-reported, GP-diagnosed conditions in both populations, and variables were generated as described in the variable harmonization table presented in Chapter 3.

4.2.2.4 Career Reflection

The career reflection of the former cricketers was analysed as a secondary measure of long-term health in this analysis. The three cricket reflection questions stated, "Considering the benefits and risks of my previous participation in cricket, I would do the same again," "Considering the benefits and risks of my previous participation in cricket, I would recommend this to my children, relatives, or close friends," and "Did your cricket career enrich your life?" As discussed in Chapter 3, the career reflection responses were divided into 3 categories of "Agree", "Undecided", and "Disagree" due to low numbers of responses in the "Undecided" and "Disagree" answer options. The 3 categories were chosen as they captured similar sentiments in the response.

Two cricketers included in this analysis did not complete the career reflection questions. These players were not excluded from this analysis as the career reflection questions were a secondary outcome measure. Both players indicated that they had OA, and one of the two indicated that they had had a stroke.

4.2.2.5 Statistical Methods

Stata 14.2 was used for calculating prevalences and for chi-squared tests and t-tests; Microsoft Excel was used for standardisation and to calculate SMRs and 95% confidence intervals in this analysis.

4.2.2.5.1 Prevalence

Prevalence values of the chronic conditions were calculated using complete case analysis for the matched former cricketer and general populations. Prevalences of THR and TKR for both populations were reported for those aged 60 years and over. Percentages and 95% confidence intervals were calculated.

4.2.2.5.2 Inclusion Criteria

Chi-squared tests and t-tests were used in order to determine whether the demographics of participants included in matched analysis, apart from age, significantly differed from those excluded due to the inclusion criteria. Variables other than age, such as smoking status or BMI, may affect chronic conditions; cricket-specific variables were also of interest in the former cricketers. This analysis addressed the additional generalizability bias introduced by the age inclusion criteria, and ensured that these demographic variables were not disproportionately represented in the age-restricted participant samples. A two-sample t-test, assuming unequal variance, was used to compare the continuous variables of age and BMI, as well as years since retirement from cricket in the former cricketers. A chi-squared test was used to compare the categorical variables of smoking status and ethnicity, and playing position in the former cricketers.

4.2.2.5.3 Comparability

Chi-squared tests and t-tests were also used to compare the demographics of the former cricketers included in matched analysis (aged 50 and over) with those of the general population sample (ELSA). This was done to ensure that the two populations had comparable demographics, in addition to the matching based on age and BMI.

4.2.2.5.4 Standardised Morbidity Ratios

Standardised Morbidity Ratios (SMRs) were calculated in order to compare prevalences of the chronic conditions between the former cricketers and general population (ELSA).

As these populations were recruited separately, as part of two distinct studies, SMRs were the appropriate analysis for this comparison.

The cricketer and ELSA populations were standardised by age and BMI. Participant age for both general and cricketer populations was categorized into 10-year bands, starting with 50 – 59 years and ending with 80 – 89 years. Participant BMI for both general and cricketer populations was categorized into the World Health Organization's principal cut-off points for Normal (18.5 – 25), Overweight (25 – 30), and Obese (30+) (121). WHO obesity class categories were not used due to small sample sizes in the former cricketer sample. Indirect standardisation was used due to some strata with small sample sizes and even one stratum with a sample size of zero. The former cricketers were the "study" population and the general population was the "standard" population, as discussed in Chapter 3.

While SMRs can be presented as ratios, they have been presented here in decimal form with 95% confidence intervals (CI). An SMR of 1.0, or with a CI that crosses 1.0, suggests no significant difference in prevalences. In this study, an SMR greater than 1.0 with a CI that did not cross 1.0 suggested a significantly greater prevalence in the former cricketers than in the general population. Conversely, an SMR less than 1.0 with a CI that did not cross 1.0 suggested a significantly lower prevalence in the former cricketers than the general population.

4.2.2.5.5 Post Hoc Analysis: OA and Depression

Due to the high prevalences of depression and OA in the former cricketers, a post hoc analysis investigated the potential relationship between depression and OA. Previous research has suggested a causal link of chronic pain and OA to depressive symptoms (122,123). Further, former elite athletes have been shown to have a significant association between OA and symptoms of common mental disorders, where OA was the

independent variable (13). Univariate logistic regression was used to explore whether the participants that reported OA, the independent variable, were more likely to report depression, the dependent variable, than participants that did not report OA. Separate logistic regression models were used for the general population and the former cricketers aged 50 and over.

4.2.2.5.6 Post Hoc Analysis: Smoking Status

Due to a significant difference between the former cricketers and general population regarding smoking status, a post hoc analysis investigated the potential impact of smoking status on SMRs. Smoking status is known to be causally associated with cardiovascular conditions, and was also significantly different between the former cricketer and general populations. The SMRs were originally matched on only age and BMI, as they are the most standard confounders for chronic conditions. However, because indirect standardisation allows for very small strata, it was possible to further stratify by smoking status in post hoc analysis. Therefore, all SMRs were recalculated, matching on age, BMI, and smoking status, to determine whether smoking status made a significant difference to reported SMRs.

4.3 Results

4.3.1 Prevalence of Chronic Conditions in Cricket (Complete Cricket Sample)

From the 202 former cricketers recruited, 36 were excluded due to missing data and 1 female cricketer was excluded, leaving 165 male cricketers to be included in the prevalence analysis for the complete cricket sample.

4.3.1.1 Subject Characteristics

The subject characteristics of the cricketer sample, as well as those of the male cricketers excluded due to missing data, are shown in Table 4.1.

4.3.1.1.1 Missing versus Non-missing

A missing versus non-missing analysis compared the subject characteristics of the cricketers with and without missing data. Two-sample t-tests for continuous variables and chi-squared tests for categorical variables did not show the characteristics to be significantly different for missing versus non-missing cricketers ($p>0.05$).

Table 4.1. Subject characteristics of the cricketers included in prevalence analysis for the complete cricket sample and of the male cricketers excluded due to missing data.

Characteristic	Cricketers *(N=165)*	Excluded male cricketers (missing data)
Age (years)		*(N=23)*
Mean (SD)	57.2 (14.2)	57.3 (15.0)
Range	28 - 88	35 - 81
Body mass index		*(N=22)*
Mean (SD)	27.6 (3.6)	26.8 (2.9)
Range	21.6 - 53.1	21.4 - 31.7
Smoking Status		*(N=22)*
Current Smoker	9 (5.5%)	2 (9.1%)
Does not smoke	137 (83.5%)	17 (77.3%)
Ex-Smoker	18 (11.0%)	3 (13.6%)
Ethnicity		*(N=22)*
White	156 (95.7%)	19 (86.4%)
Black, Asian, or Mixed	7 (4.3%)	3 (13.6%)
Playing Position		*(N=17)*
Batsman	43 (26.1%)	2 (11.8%)
Wicketkeeper	18 (10.9%)	1 (5.9%)
Fast Bowler	78 (47.3%)	12 (70.6%)
Spin Bowler	26 (15.7%)	2 (11.8%)
Years since retirement from cricket [mean (SD)]	24.9 (13.7)	*(N=17)* 24.5 (12.3)

4.3.1.2 Prevalence

The percentages and 95% CI for each chronic condition prevalence in the cricketer population are shown in Figure 4.1. The most common condition was OA, with a

prevalence of 44.2%. Heart problems had a prevalence of 9.7%. No cricketers reported a diagnosis of dementia.

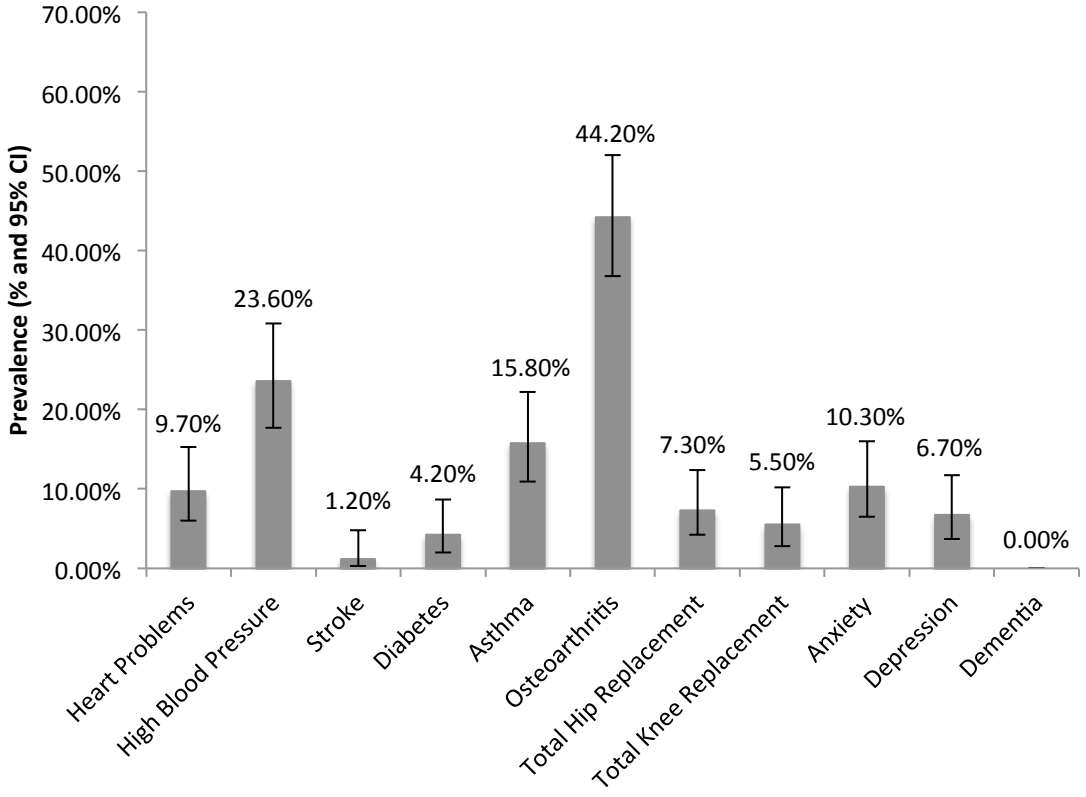


Figure 4.1. Percentages and 95% CI for each chronic condition in the former cricketer sample (N=165).

4.3.2 Comparison of Former Cricketer Chronic Conditions with General Population

Figure 4.2 shows how the samples from the former cricketer and the general populations were determined for matched analysis. After inclusion criteria were applied, 113 cricketers and 4496 general population participants remained for SMR analysis.

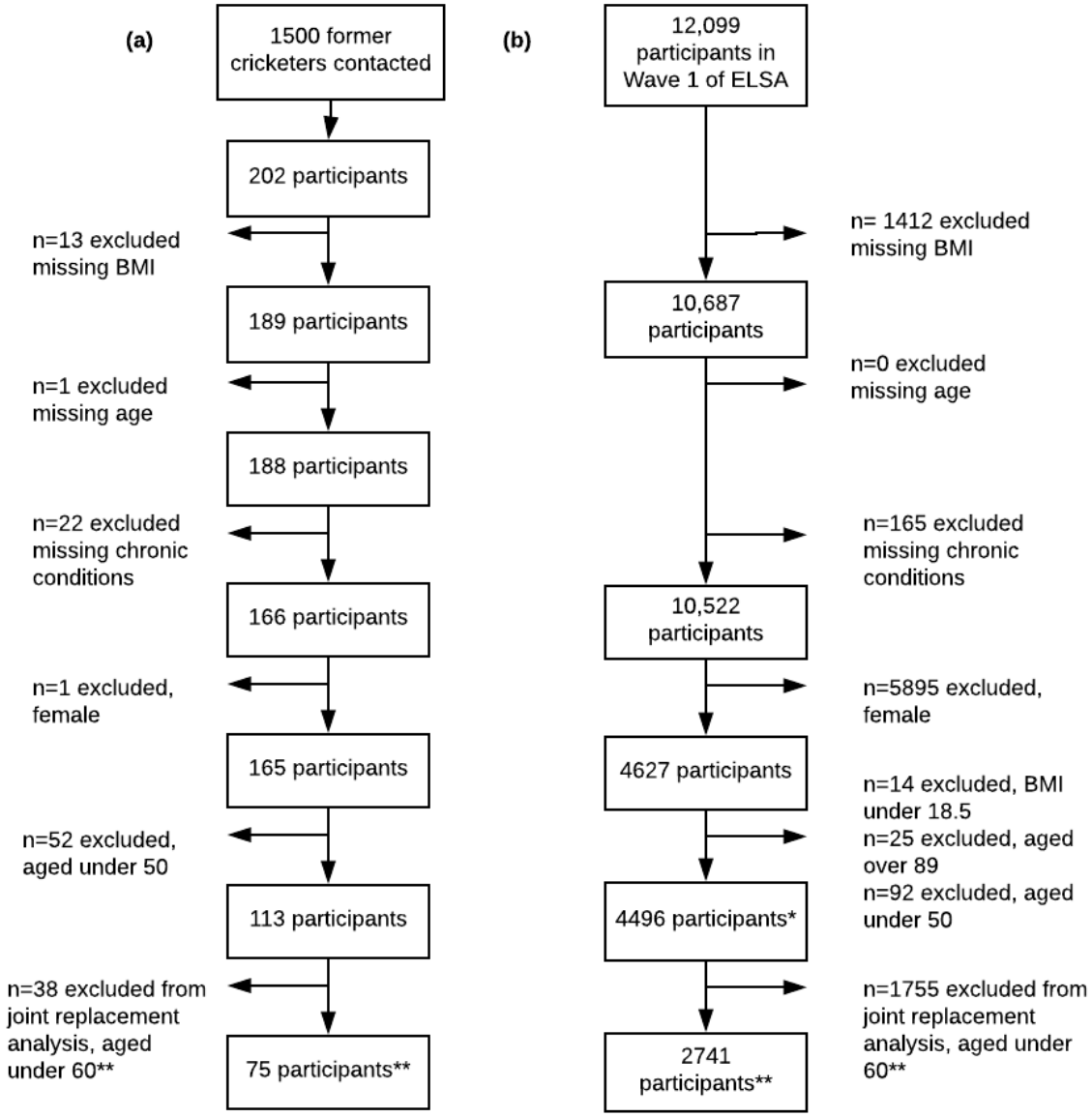


Figure 4.2. (a) Former cricketers included in analysis, from recruitment to final sample size; (b) general population (ELSA Wave 1 participants) included in analysis.
***General population participants aged 50 and over, and matched for age and BMI with former cricketers**
****General population participants aged under 60 were not asked joint replacement questions (THR, TKR); therefore, participants aged 60 and over in both population samples were matched for THR and TKR.**

4.3.2.1 Subject Characteristics

The subject characteristics of the former cricketers and general population participants included in analysis are presented in Table 4.2, alongside the characteristics of those participants from each population excluded due to the inclusion criteria of male, aged 50 to 89, and with a BMI of at least 18.5.

4.3.2.1.1 Inclusion Criteria

The subject characteristics were compared within each population for those with complete data, before and after the inclusion criteria were applied. Apart from age and time since retirement, no significant difference was found between the former cricketers excluded from analysis due to age (n=52) versus those included in the analysis (n=113). However, the general population participants excluded from analysis due to the inclusion criteria were significantly different from those included with respect to smoking status ($p<0.001$) and ethnicity ($p<0.05$). The general population participants included in SMR analysis had fewer ex-smokers and more participants that had never smoked, and fewer non-white participants than those participants excluded from analysis.

4.3.2.1.2 Comparability

The demographics of the former cricketers and general population participants included in SMR analysis were also compared. This analysis showed the general population (n=4496) to be significantly different from the former cricketers (n=113) for smoking status ($p<0.001$). Fewer former cricketers than the general population were ex-smokers or currently smoked.

Table 4.2. Subject characteristics of former cricketer and general (ELSA) populations included in matched analysis, and of those in each population excluded from analysis due to inclusion criteria. A star (*) indicates a significant difference within each population (included versus excluded). A dot (°) indicates a significant difference between populations (cricketers versus general population).

Characteristic	Former Cricketers *(N=113)*	Normal population *(N=4496)*	Excluded cricketers (inclusion criteria) *(N=52)*	Excluded normal (inclusion criteria) *(N=6026)*
Age (years)				
Mean (SD)	65.1 (9.1)*	64.2 (9.6)*	40.2 (6.0)*	63.4 (11.6)*
Range	50 - 88	50 - 89	28 - 49	31 - 99
Body mass index				
Mean (SD)	27.9 (4.0)	27.6 (3.8)	27.0 (2.3)	27.5 (5.1)
Range	21.6 - 53.1	21.4 - 53.1	21.4 - 32.6	14.8 - 55.1
Smoking Status				
Current Smoker	6 (5.4%)°	775 (17.4%)*°	3 (5.8%)	1125 (18.9%)*
Does not smoke	92 (82.1%)°	1170 (26.3%)*°	45 (86.5%)	2603 (43.7%)*
Ex-Smoker	14 (12.5%)°	2510 (56.3%)*°	4 (7.7%)	2228 (37.4%)*
Ethnicity				
White	107 (96.4%)	4358 (96.9%)*	49 (94.2%)	5873 (97.6%)*
Black, Asian, or Mixed	4 (3.6%)	138 (3.1%)*	3 (5.8%)	144 (2.4%)*
Playing Position				
Batsman	34 (30.1%)	---	9 (17.3%)	---
Wicketkeeper	11 (9.7%)	---	7 (13.5%)	---
Fast Bowler	51 (45.1%)	---	27 (51.9%)	---
Spin Bowler	17 (15.1%)	---	9 (17.3%)	---
Years since retirement from cricket [mean (SD)]	30.6 (11.4)*	---	10.5 (6.5)*	---

A star (*) indicates a significant difference within each population (included versus excluded). A dot (°) indicates a significant difference between populations (cricketers versus normal).

4.3.2.2 Prevalence

The prevalence of heart problems in the former cricketer and general populations analysed was 13.3% and 23.1%, respectively (Figure 4.3). In the former cricketers analysed, 31.9% reported high blood pressure, compared to 36.4% of the general population. The prevalence of OA in any joint was 51.3% in the analysed former cricketers and 13.4% in the general population. The prevalence of anxiety and depression in the former cricketers was 12.4% and 8.8%, respectively, compared to 3.4% and 4.2%

anxiety and depression reported in the general population. No former cricketers reported a diagnosis of dementia.

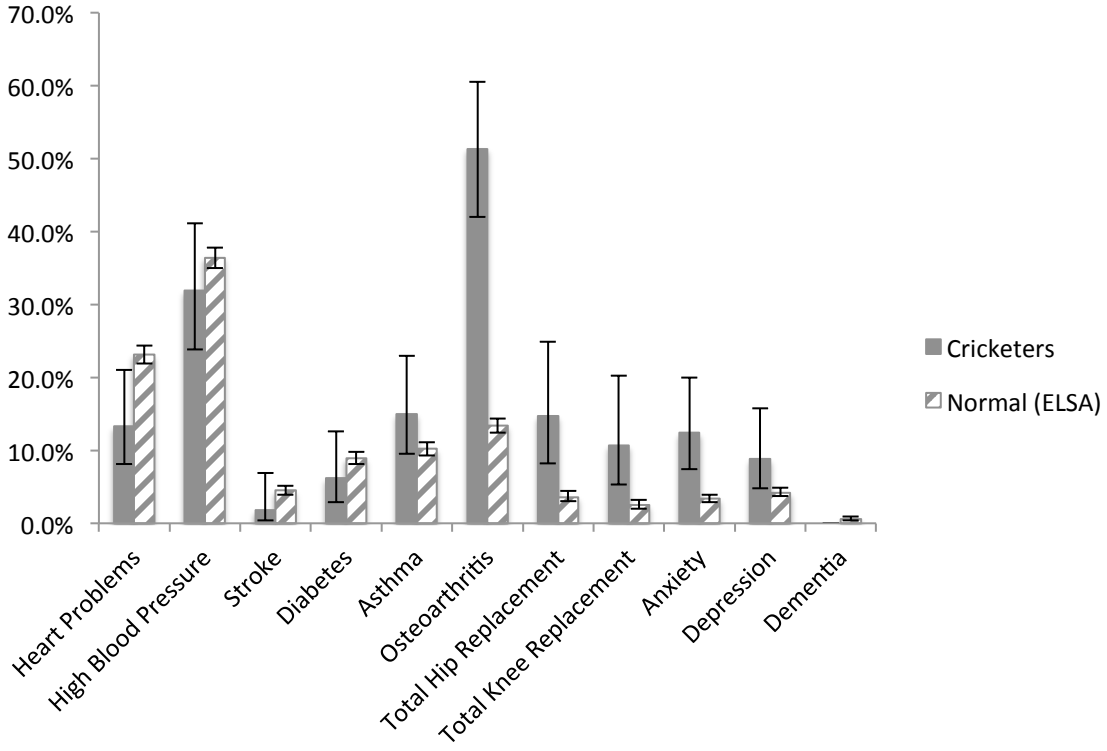


Figure 4.3. Prevalence and 95% CI for each chronic condition in the former cricketers and general population (ELSA) included in matched, SMR analysis.

4.3.2.3 Standardised Morbidity Ratios

The age- and BMI-matched SMRs and 95% confidence intervals are shown in Table 4.3. 45% fewer of the former cricketers reported heart problems than the general population, with an SMR of 0.55 (0.33-0.91). The former cricketers reported 3.6 times the OA, 4.0 times the THR, and 3.8 times the TKR of the general population (SMRs of 3.64 (2.81-4.71), 3.99 (2.21-7.20), and 3.84 (1.92-7.68), respectively). The former cricketers reported 4.0 times the anxiety and 2.2 times the depression of the general population (SMRs of 3.95 (2.34-6.67) and 2.22 (1.2-4.14), respectively).

Table 4.3. Age- and BMI-matched SMRs for chronic conditions in the former cricketer population compared to the general population (ELSA).

Outcome	Cricketers, N*	ELSA, N*	Age- and BMI-adjusted SMR	95% CI
Heart Problems	**113**	**4496**	**0.55**	**0.33 - 0.91**
High Blood Pressure	113	4496	0.84	0.60 - 1.16
Stroke	113	4496	0.38	0.09 - 1.52
Diabetes	113	4496	0.65	0.31 - 1.35
Asthma	113	4496	1.47	0.91 - 2.37
Osteoarthritis	**113**	**4496**	**3.64**	**2.81 - 4.71**
Total Hip Replacement	**75**	**2741**	**3.99***	**2.21 - 7.20**
Total Knee Replacement	**75**	**2741**	**3.84***	**1.92 - 7.68**
Anxiety	**113**	**4496**	**3.95**	**2.34 - 6.67**
Depression	**113**	**4496**	**2.22**	**1.20 - 4.14**
Dementia**	113	4496	0.00	0.00
*ELSA data only has complete data for those aged 50 and over, and only has THR and TKR data for those aged 60 and over. The cricketer population for each of these outcomes has been matched accordingly, with 75 cricketers and 2741 ELSA participants in the THR and TKR outcome analysis.				
**No cricketers reported dementia				

4.3.2.4 Career Reflection

The secondary outcome for the SMR analysis was the career reflection of the former cricketers. As mentioned previously, two former cricketers did not complete the career reflection questions; they were not excluded from matched analysis because career reflection was a secondary outcome. The responses of each career reflection question were categorised into "agree", "undecided", and "disagree". The prevalence of each response category for each question is shown in Figure 4.4. Over 97% of former cricketers included in the SMR analysis reported that they would do the same again, when asked to reflect on the benefits and risks of their career in cricket.

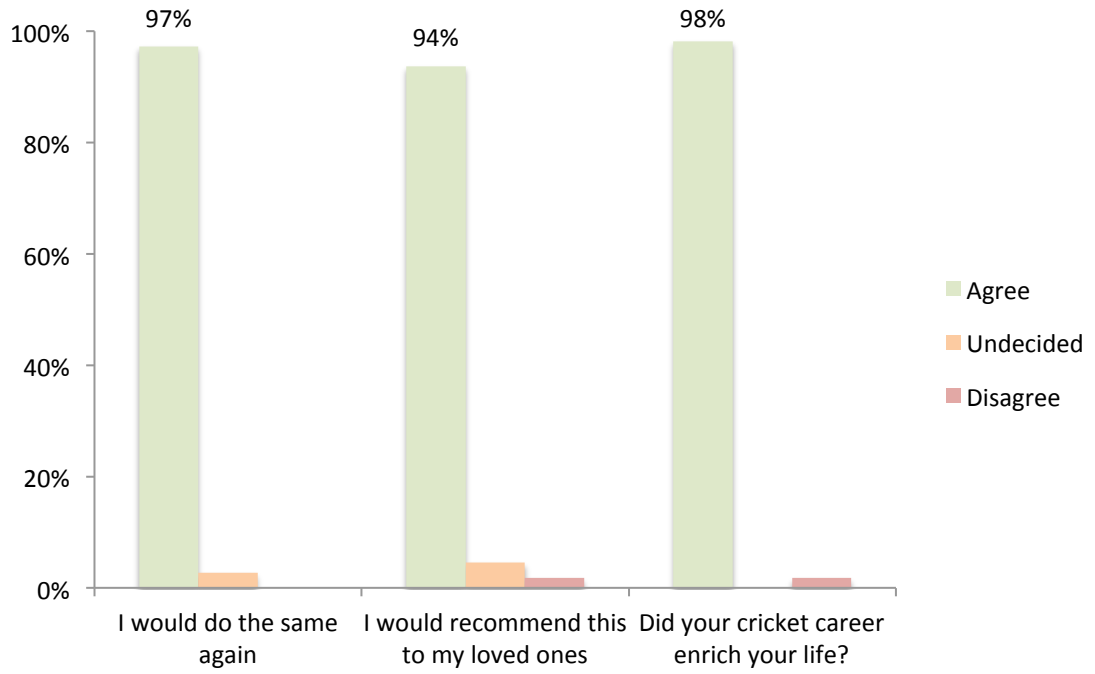


Figure 4.4. Prevalence of each response category for the career reflection questions (N=111).

4.3.2.5 Post Hoc Analysis: OA and Depression

Due to the high prevalences of depression and OA in the former cricketers, a post hoc analysis investigated the relationship between depression and OA in both the former cricketer and general populations included in SMR analysis. Univariate logistic regression did not show a significant association between depression and OA in the former cricketers, with an odds ratio (OR) of 0.87 (95% CI -0.54 – 2.27). The general population, however, showed that reported OA had a significant, negative association with depression, with an OR of 0.40 (95% CI 0.02 – 0.78).

4.3.2.6 Post Hoc Analysis: Smoking Status

Due to the causal association smoking status has been shown to have on some of the chronic conditions investigated, such as heart problems, and the significant difference in smoking status found between the former cricketers and general population, a post hoc analysis investigated the potential effect of smoking status on the SMR analysis. For this analysis, one former cricketer, aged 70, was excluded due to missing smoking status. The

effect size of some SMRs changed when adjusting for smoking status, in addition to adjusting for age and BMI. For example, the SMR for heart problems went from 0.55 (0.33 – 0.91) to 0.59 (0.35 – 0.99) when smoking status was included in matching. However, including smoking status in matching did not make any significant SMRs become non-significant. The SMRs, adjusted for age, BMI and smoking status, are shown in Table 4.4.

Table 4.4. Age-, Smoking-, and BMI-matched SMRs for chronic conditions in the former cricketer population compared to the general population (ELSA).

Outcome	Cricketers, N*	ELSA, N*	Age-, Smoking- and BMI-adjusted SMR	95% CI	Age- and BMI-adjusted SMR	95% CI
Heart Problems	**112**	**4455**	**0.59**	**0.35 - 0.99**	**0.55**	**0.33 - 0.91**
High Blood Pressure	112	4455	0.83	0.59 - 1.15	0.84	0.60 - 1.16
Stroke	112	4455	0.38	0.09 - 1.50	0.38	0.09 - 1.52
Diabetes	112	4455	0.65	0.29 - 1.46	0.65	0.31 - 1.35
Asthma	112	4455	1.48	0.91 - 2.41	1.47	0.91 - 2.37
Osteoarthritis	**112**	**4455**	**4.15**	**3.21 - 5.37**	**3.64**	**2.81 - 4.71**
Total Hip Replacement	**74**	**2713**	**4.35**	**2.41 - 7.85**	**3.99***	**2.21 - 7.20**
Total Knee Replacement	**74**	**2713**	**4.02**	**2.01 - 8.03**	**3.84***	**1.92 - 7.68**
Anxiety	**112**	**4455**	**3.65**	**2.16 - 6.17**	**3.95**	**2.34 - 6.67**
Depression	**112**	**4455**	**2.41**	**1.30 - 4.48**	**2.22**	**1.20 - 4.14**
Dementia**	112	4455	0.00	0.00	0.00	0.00
*The sample sizes for both former cricketers and ELSA have been reduced in this post hoc analysis due to missing smoking status data.						
**No cricketers reported dementia						

4.4 Discussion

This research is the first to take a comprehensive assessment of the long-term health of former cricketers. Cardiac outcomes were decreased in former cricketers compared to the general population, a significant increase was found in former cricketers in musculoskeletal and mental health conditions compared to the general population, and the majority of former cricketers felt that their life was improved by their involvement in the sport.

4.4.1 Cardiovascular Conditions, Diabetes, and Dementia

The prevalence of heart problems was significantly lower in the former cricketers than the general population, with an SMR of 0.55, suggesting a protective effect for the former cricketers. This is consistent with existing literature, given the wide number of studies reporting decreased rates of CHD and other cardiovascular outcomes with increased physical activity (8,15–18,124). It is noted that the question posed to the general population listed specific cardiovascular conditions, which may have been expected to underestimate the prevalence of heart problems due to participants not recognizing a condition with which they have been diagnosed. However, the prevalence of heart problems in the general population included any of these listed cardiovascular conditions. Further, the general population was presented with an option of "any other heart trouble". This option is expected to make the question posed to the general population comparable to the question posited to former cricketers, which listed only "heart problems", and ensure the prevalence of heart problems was not underestimated in the general population.

The SMRs were not significant for high blood pressure and diabetes, but trended toward a potential lower prevalence of these conditions in the former cricketers than the general population. This would be consistent with current literature, as high blood pressure and diabetes are often associated with presence of cardiovascular conditions, which were lower in the former cricketers, and are beneficially influenced by physical activity (8,14,16). The SMR for stroke was also non-significant, though this is a condition that would have been expected to see the same positive impact of physical activity as heart problems and high blood pressure.

For high blood pressure, diabetes, and stroke, a larger sample size of former cricketers may have improved the strength of these SMRs. While smoking status was significantly

different between the former cricketers and general population, and this would be expected to most strongly impact SMRs for conditions such as heart problems, high blood pressure, and stroke, post hoc analysis did not show a significant affect of smoking status on the SMRs for these, or any other, conditions.

Dementia was not reported by any former cricketers in this study; this may be due to a selection bias, as the study was primarily advertised by email.

4.4.2 Musculoskeletal Outcomes

The prevalence of OA was significantly higher in this former elite cricketer population than in the general population with an SMR of 3.64 (2.81 – 4.71), consistent with research of other former elite athletes. A meta-analysis of 20 studies of elite athletes compared with a control group found an increased risk of OA in former elite athletes with a risk ratio of 1.31 (2). One reason for the former cricketers to have a higher prevalence of OA than the general population may be joint injury, as this is one of the strongest risk factors for OA (3,12). Elite athletes tend to see high rates of injury with the intensity of their training and competition. Important to note, though, is that these injury rates depend on the sport. While In injury surveillance studies of current players, elite football players had injury incidence rates of 77.3 injuries per 1000 player-hours, elite cricketers had injury rates ranging from 1.39 to 4.87 injuries per 1000 player-hours. Rugby union has catastrophic injury incidence between 0.89 to 2.00 per 100,000 players, but the rates in cricket are currently unknown (125–127). These injury incidence rates are for current players; due to the retrospective, self-report nature of this study, player-hour metrics were not collected. However, it is not expected that the former cricketers in this study would have significantly different injury rates than those of the players included in the cited injury surveillance studies.

A more definitive measure of OA can be TJR, because it is most often a treatment for advanced OA. Self-reported, GP-diagnosed OA can be underestimated due to the lack of a diagnosis, or overestimated due to a participant's confusion of OA with other conditions. TJR is a more reliable self-reported measure of OA because it is a memorable, distinct event; it is a major surgery and it usually results in significant improvement for patients' joint pain (128). The limitation with TJR as a measure of OA is that it can also be a treatment for rheumatoid arthritis or a traumatic injury, though TJR is most often a treatment for OA. The higher prevalence of TJR in the population of former cricketers than in the general population, aged 60 and over due to the data collection of the general population, may indicate more advanced OA in the former cricketers. It also supports the increased OA finding as a true result.

There are, however, a few factors relevant to this population that may have contributed to an even higher reported prevalence of OA and TJR in the former cricketer population. The prevalence of OA may have been overestimated in the former cricketers because the phrase "wear and tear" is commonly used by medical professionals that work with cricketers, and is not always meant as a diagnosis of OA. Elite athletes may also be more likely to receive a diagnosis of OA or treatment with a TJR because they are more likely to have access to and be seen by a doctor. The former cricketers may also be more likely to seek treatment or a TJR in order to maintain activity. These factors may have overestimated the degree of increased prevalence of OA and TJR in the former cricketers.

4.4.3 Mental Health Outcomes

Prevalence of anxiety and depression were significantly higher in the matched former cricketers, at 12.4% and 8.8%, respectively, compared to 3.4% and 4.2% for anxiety and depression in the general population. Recent UK estimates for anxiety prevalence in the general population was 6.6%, much higher than this general population sample's

prevalence of 3.4%, and estimates for depression prevalence was 3.8%, which is lower than this general population sample's prevalence of 4.2% (129).

A recent study of current and former professional South African cricketers found 4-week prevalence of symptoms of anxiety and depression to be 37% in current cricketers and 24.3% in former cricketers, higher than the prevalences reported here (33). Importantly, the symptoms of anxiety and depression were assessed in the South African cricketers, which may be more sensitive than this study's measure of lifetime clinical diagnoses.

Previous studies of Australian, French, and German current elite athletes showed comparable rates of mental health conditions to the general population (29–31). The former cricketers' significantly higher prevalence of anxiety and depression may appear more concerning in comparison with these studies. However, the previous studies evaluated current elite athletes, whereas this study has captured former athletes and asked if they "had ever had" a diagnosis of anxiety or depression. It is possible that some of these cricketers' mental health diagnoses may have come after retirement from elite sport. It is known within the sport that some players experience a temporary bout of depression after retirement, though players several years later may not express that they "currently" have depression. Therefore, as this study has asked former cricketers if they "ever had" a diagnosis of anxiety or depression, these estimates would be expected to be higher than if the cricketers were asked if they "currently have" anxiety or depression. This raises the importance of future studies not only asking if the participant "has ever had" a diagnosis of anxiety or depression, but also if they "currently have" anxiety or depression. Further, the PCA has done a great deal of work in the last 5 years to raise awareness of and foster openness about mental health in former cricketers. The reported prevalences of anxiety and depression in the former cricketers, therefore, may be an indication of this work.

It was hypothesized that, as previous research has shown, part of the high prevalence of depression may be explained by the pain associated with a high prevalence of OA. However, the post hoc analysis regarding depression and OA did not yield a significant association in the former cricketers aged 50 and over. A significant association between diagnosed OA and depression was found in the general population. However, this was a negative association, suggesting that those who reported OA were less likely to report depression than those who did not report OA. This was an unexpected result, inconsistent with the existing literature. It is possible that depression was simply under-reported in the general population. For the former cricketers, the non-significant association may be due to a lack of power. As it is recognized that injury history, pain and OA play a role in anxiety and depression rates for elite athletes, the relationship between mental health conditions and OA in former elite athletes may warrant further analysis (13,29,130,131).

4.4.4 Career Reflection Questions

Of further note are the career reflection measures in this study, which support the model of separating mental health into two distinct categories of mental illness and mental health (132). Keyes et al propose that the presence of mental illness, such as anxiety or depression, does not "imply the absence of mental health" (133). It is important, therefore, to investigate not only a clinical diagnosis of a mental illness, but also to explore the mental health, or wellbeing, of a population. While the rates of diagnosed anxiety and depression were higher than the general population, the vast majority of former cricketers reflected positively on their cricket career. Over 98% of former cricketers felt that cricket "enriched" their lives and no former cricketers felt, upon reflection of the benefits and risks of their career in cricket, that they would not do the same again. Additionally, over 93% of former cricketers agreed that they would

recommend their career in cricket to their loved ones. This reflects the clear outweighing of benefits over the risks in cricket, even at the elite level.

4.4.5 Limitations

The former cricketer population was significantly different to the general population in smoking status, which may reflect a positive culture in elite cricketers, and elite athletes generally. This difference may also be due to the general population data collection being 12 years prior to the cricketer data. The Office of National Statistics shows that smoking among UK men was at 17.7% in 2016 compared with 26% in 2004, having steadily declined since recording began in 1974 (134,135). This societal declining trend in smoking may have decreased the likelihood of the former cricketers ever smoking, as they will have been born 12 years after their age-standardised general population counterparts. Whatever the reasons for the difference in smoking status between former cricketers and the general population, the post hoc SMR analysis, adjusting for age, BMI, and smoking status, showed that the effect size for heart problems only increased by 0.04 and the SMR remained statistically significant. The smoking status-adjusted SMR for heart problems was of particular interest, given the causal association between these variables. The adjustment for three variables required very small strata and several strata with zero cricketers in standardisation. Such strata made the SMRs less stable, which is why the original SMR analysis only adjusted for age and BMI.

While this is the largest cohort of former elite cricketers for the study of long-term health outcomes, the 13% response rate limits generalizability to all cricketers. Although these cricketers' age distribution was representative of the PCA's entire former player population, we cannot exclude selection bias. Former cricketers with health problems may be more likely to complete the questionnaire, leading to an overestimation of the

prevalence and risk of conditions in the former cricketers. However, the decreased risk of heart problems argues against this as a major bias.

The general population sample used for SMR analysis required the exclusion of all former cricketers aged under 50. As found in the SMR for high blood pressure, the exclusion of these younger participants decreased the power of some results. Further, the general population sample excluded participants aged under 60 years in questions regarding joint replacement. Tveit et al suggest that elite athletes may have a higher risk of requiring a joint replacement and at a younger age than the general population (136). However, due to the exclusion of participants aged under 60 years in the general population (ELSA), such an analysis is prevented here. Therefore, the power of this study's results and their generalizability were limited.

The former cricketer population excluded the only female participant. Women's professional cricket is relatively new, so the number of women that have played cricket at higher than a recreational level in the UK is very low. However, the wider recruitment of former female cricketers would help to gain a fuller picture of the long-term impacts of cricket.

Both the former cricketer and general populations were asked to self-report their chronic conditions. This could introduce a recall bias in both samples. A sample of the former cricketers consented to the research team accessing their medical records to validate responses, so future work should include the validation of the former cricketers' responses and the questionnaire.

Finally, variation in question phrasing posed to the former cricketers versus that posed to the general population may have created a potential bias in reporting. Table 3.1 showed a comparison of question phrasing and variable harmonisation. With respect to OA, it is noteworthy that only a precise self-reported diagnosis of "osteoarthritis" would

have defined a case for the general population. A previous study has shown this type of "strict" definition to have a lower sensitivity than a definition that includes other phrases, such as "joint/cartilage wearing out", that patients might use to describe their diagnosis (137). Therefore, it is possible that the definition of OA in the general population has underestimated the prevalence of OA in that sample. For anxiety and depression, the general population had to first respond positively to "Any emotional, nervous, or psychiatric problems", while the former cricketers were presented directly with the conditions "anxiety" and "depression." The extra layer of questioning for the general population, therefore, may have underestimated their prevalence of these mental health conditions. In turn, this may have overestimated the increased risk for anxiety and depression in the former cricketers.

4.5 Conclusions

This study presented the largest cross-sectional cohort of former elite cricketers in order to investigate a variety of long-term health outcomes. This population of former elite cricketers had significantly lower rates of heart problems and non-significant but lower trending rates of high blood pressure and diabetes than the general population sample. These former cricketers also had higher rates of OA, THR, TKR, anxiety and depression than the general population sample. Over 97% of former cricketers, though, agreed with the statement that they would "do the same again" with regards to their cricket career. Future studies should be conducted to explore in particular the higher rates of musculoskeletal conditions, and the mechanisms and risk factors for higher prevalence values.

4.6 Disclosure of Publications Including Portions of This Work

Portions of this work, including the prevalences and SMR results and some discussion points, have been submitted and accepted as a first author poster presentation to the OARSI World Congress 2017 and as a first author article in the Journal of Science and Medicine in Sport (138,139).

Chapter 5 Prevalence and Association of NHANES pain, GP-diagnosed OA, and Joint Replacement with Injury and Cricket-related Factors Across All Joints in Former Elite Cricketers

5.1 Introduction

As discussed in the previous chapter, lifelong physical activity has a myriad of long-term health benefits, including decreased risk of coronary heart disease, stroke, and other cardiovascular outcomes (8,15–18). However, osteoarthritis (OA) has been suggested to be more common in certain former elite athletes (2,4). The previous chapter established that GP-diagnosed OA (GP-OA) and total joint replacement (TJR) were more common in a sample of former cricketers than the normal population.

The increased prevalence of OA in former elite athletes is hypothesized to be caused by increased joint loading and risk of injury. Different playing positions in cricket would be expected to have varying loads and risk of injury, and therefore varying relationships with OA. A study of GPS data from 42 elite Australian cricketers over the course of two seasons showed that the distance covered, number of sprints, and work-to-recovery ratio varied by playing position, with fast bowlers covering the most distance and having the highest number of sprints and lowest work-to-recovery ratio (140). Injury surveillance data of elite Australian cricketers, collected over 10 seasons, found that fast bowlers also had the highest prevalence of injury (141). Study of bowling biomechanics demonstrates that bowlers experience twice the functional load during bowling in their leading leg, which is the leg that is planted before releasing the ball, than in their trailing leg, the contralateral leg planted during the run up (5).

However, no studies exist to describe the prevalence of pain, OA, and TJR in former elite cricketers, or to evaluate the relationship between injury, playing load, playing position

or the functionally dominant side with these long-term musculoskeletal outcomes. Understanding the prevalence of these musculoskeletal outcomes and their relationship to cricket-related factors can inform sport-specific risk prevention strategies.

The aim of this chapter is to describe the prevalence of joint-specific NHANES pain, GP-OA, and TJR across all joints in former elite cricketers and to analyse the association of these outcomes with injury and cricket-related factors. This aim will be addressed using the data described in Chapter 4 to report the prevalence of joint-specific and side-specific NHANES pain, GP-OA, and TJR in former elite cricketers. Further analysis will investigate the association of these musculoskeletal outcomes with injury and the cricket-related factors of cricket-related injury, number of professional seasons, playing position, and the functionally dominant side.

5.2 Methods

5.2.1 Participants

As described in Chapters 3 and 4, all members of the Professional Cricketers' Association (PCA) on the PCA's "former players" membership list were invited to participate in the study. Recruitment lasted for four months, contacting 1500 former cricketers and resulted in a response rate of 13%, with 80.2% of cricketers requesting the questionnaire completing the study.

5.2.2 Inclusion Criteria

Male former cricketers with complete data for age, BMI, the three musculoskeletal outcomes, and the cricket-related variables of interest were included in this analysis. The musculoskeletal outcomes of interest were NHANES pain, OA, and TJR. The cricket-

related variables were injury and cricket-related injury, number of professional seasons, playing position, and the functionally dominant side.

5.2.3 Independent variables

Demographic variables analysed in this sample of former cricketers were age, BMI, smoking status and ethnicity. Mean years since retirement from cricket was also reported. These variables were generated as detailed in Chapter 3.

5.2.3.1 Cricket-Related Variables

Most of the cricket-related variables were also generated as described in Chapter 3. Variables generated differently for this chapter are detailed below; key details for the remaining variables are repeated for reference.

5.2.3.1.1 Injury and Cricket-Related Injury

Injury and cricket-related injury were generated as described in Chapter 3. Only severe injuries were collected. A severe injury was defined as an injury leading to more than 4 weeks of reduced participation in exercise, training or sport. Injuries and cricket-related injuries were recorded for the spine, shoulder, elbow, finger/hand, wrist, hip/groin, knee, and ankle. Side-specific injuries were collected but only joint-specific cricket-related injuries were collected. For example, a participant may report that they have had a cricket-related shoulder injury, but the questionnaire did not collect whether this cricket-related shoulder injury was on the left or right side. This cricket-related shoulder injury, therefore, would be used as a person-level predictor for an outcome of interest in either shoulder.

5.2.3.1.2 Playing Position

Playing position was categorized differently for this analysis than described in Chapters 3 and 4. Due to a lack of cases in each categorization used previously, responses were categorized into “Batsman” and “Bowler”. Physicians for elite cricketers also advised

that this categorization would be more clinically relevant for musculoskeletal outcomes. "Batsman" included those that would have been classified as a "batsman" in the previous chapter; "bowler" included those that would have classified as a "fast bowler" or "spin bowler" in the previous chapter, including all-rounders. Two analyses were run to determine how to treat "wicketkeepers", as described in the statistical methods section of this chapter.

5.2.3.1.3 Number of Professional Seasons

As described in Chapter 3, number of professional seasons was generated to capture playing load. The metric of playing load was intended to quantify load due to elite cricket, so the number of professional seasons captured the most intense period of cricket training and playing for a former elite cricketer.

5.2.3.1.4 Functionally Dominant Side

Functionally dominant side was generated as described in Chapter 3. This variable was only used in a subanalysis of the lower limb outcomes in bowlers, as "bowlers" have been classified in this chapter. Functionally dominant side for bowlers defined the "dominant" side as the leading lower limb during bowling. For example, right-handed bowlers had a "dominant" left leg and a "non-dominant" right leg.

5.2.4 Outcome variables

Three outcome variables were of interest: NHANES pain, GP-OA, and joint replacement. These variables were generated as described in Chapter 3, with joint- and side-specific variables generated for each of the outcomes. NHANES pain was defined as pain in a joint on most days of the last month. GP-OA was captured with the question "Have you ever been told you have wear and tear, degeneration, or osteoarthritis by a doctor?" Joint replacement was captured with the question "Have you ever had a joint replacement?"

5.2.4.1 Poor Joint Outcome

As mentioned in Chapter 3, poor joint outcome was defined as a positive response to any of NHANES pain, GP-OA, or joint replacement at a joint. This synthesized variable increased the power of results and provided a more clinically relevant measure of joint trouble for a participant. This variable reflected that at some point in the participant's life, they experienced long-term pain, had a diagnosis of OA, or had a joint replacement.

5.2.5 Statistical methods

Stata 14.2 was used for all statistical analysis in this study.

5.2.5.1 Missing versus Non-Missing

Chi-squared tests and t-tests were used to compare the subject characteristics of participants included in analysis with complete data versus participants excluded due to missing information. This analysis evaluated how representative the sample of former cricketers was of the entire former cricketer sample.

5.2.5.2 Treatment of "Wicketkeepers"

For analyses using the playing position variable, two analyses were run to determine how to treat "wicketkeepers". The first analysis excluded wicketkeepers from analysis; the second included them as "batsmen" to increase the power of the results. The results of these two analyses were assessed to determine whether a significant difference existed between the different treatments of wicketkeepers.

5.2.5.3 Association of Cricket-related Variables

The association among the cricket-related variables was tested using chi-squared and Wilcoxon-Mann-Whitney tests, where appropriate. Wilcoxon-Mann-Whitney tests were used for number of professional seasons, as this variable was positively skewed. Associations were tested to evaluate the independence of these variables.

5.2.5.4 Prevalence

Prevalence values of joint-specific NHANES pain, GP-OA, joint replacement, and cricket-related injury were calculated using complete case analysis. Side-specific prevalence was calculated for NHANES pain, GP-OA, and joint replacement. Prevalence and 95% confidence intervals were calculated.

5.2.5.5 Sensitivity and Specificity of OA Outcomes

Sensitivity and specificity analyses were used to evaluate the level to which NHANES pain identified participants with GP-OA, and similarly for GP-OA identifying participants with joint replacement. As inclusion of the three musculoskeletal outcomes was intended to ensure that OA was captured at any stage of progression, the sensitivity and specificity of these outcomes indicated how the measures overlapped.

5.2.5.6 Multivariable Logistic Regression

Logistic regression was used to test the association of the cricket-related variables with the binary outcome variable of poor joint outcome for each joint.

5.2.5.6.1 Confounding

Confounding variables included BMI, age, and injury.

While age and BMI did not have a clear independent association with all of the exposure variables, all of the logistic regression models were adjusted for both due to their strong causal associations with the outcome variables.

Injury was only adjusted for within the model for number of professional seasons and playing position, due to the independent association that may exist between these variables.

5.2.5.6.2 Events per Predictor

As mentioned in the Methods chapter, it is common practice that logistic regression should only be used when at least 10 events per predictor (EPV) exist. Research suggests,

however, that statistically significant results with 5 – 9 EPV can still yield confidence interval coverage within acceptable levels (119). Due to the sample size of this study, the threshold for running a logistic regression model was 5 or more EPV. Models with fewer than 5 EPV were classified as "unstable" and results were not reported.

5.2.5.7 Generalized Estimating Equations (GEE)

GEE analysed side-specific injury and side-specific functionally dominant side as a predictor for side-specific poor joint outcome, clustered by participant and side. GEE were used due to the inability to meet the logistic regression assumption of independence of observations for side-specific data for the same participant, e.g. left and right knees.

5.2.5.8 Post Hoc Analysis: Functionally Dominant Side

The functionally dominant side of bowlers did not appear to have a significant association with poor joint outcomes, which was an unexpected result. To investigate this cricket-related variable further, post hoc analysis described the side-specific prevalence of injury, pain, and OA in the lower-limb of bowlers, stratified by functionally dominant side.

5.3 Results

The flowchart in Figure 5.1 shows how the sample from the former cricketers was determined for this analysis. After inclusion criteria were applied, 152 cricketers remained for analysis.

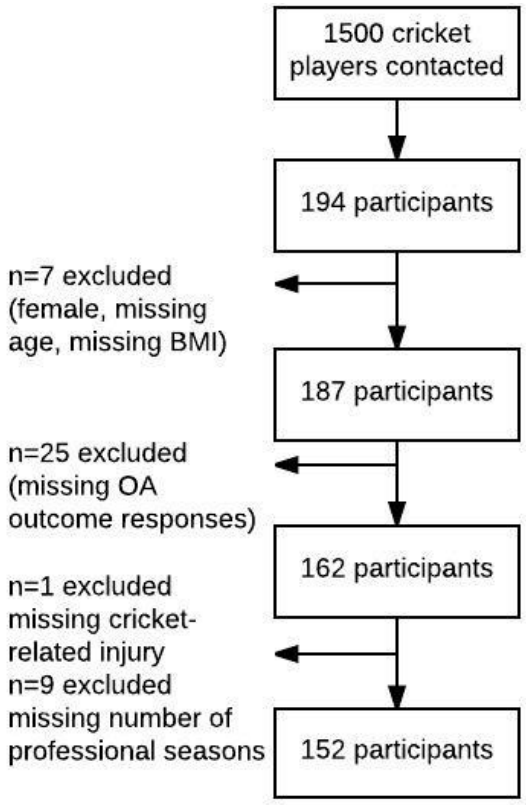


Figure 5.1. Former cricketers included in MSK analysis, from recruitment to final sample size.

5.3.1 Subject Characteristics

Table 5.1 shows subject characteristics of the former cricketer sample included in analysis and of those participants with missing data.

5.3.1.1 Missing versus Non-Missing

Two-sample t-tests for continuous variables and chi-squared tests for categorical variables demonstrated that the characteristics of those participants excluded from the analysis due to missing data did not significantly differ from those included in the analysis ($p>0.05$).

Table 5.1. Subject characteristics for cricketers included in analysis (N=152) and those excluded due to missing data (N=42). The *N* for the missing cases is shown above each characteristics.

Characteristic	Former Cricketers in analyses (N=152)	Participants missing independent or outcome variables
Age (years)		N=38
Mean (SD)	57.0 (14.4)	57.1 (14.5)
Range	28 - 88	32 - 81
Body mass index		N=36
Mean (SD)	27.5 (3.6)	27.6 (3.2)
Range	21.6 - 53.1	21.4 - 35.4
Smoking Status		N=41
Current Smoker	8 (5.3%)	3 (7.3%)
Does not smoke	125 (82.8%)	35 (85.4%)
Ex-Smoker	18 (11.9%)	3 (7.3%)
Ethnicity		N=40
White	144 (95.4%)	36 (90.0%)
Black, Asian, or Mixed	7 (4.6%)	4 (10.0%)
Playing Position		N=36
Batsman	39 (25.7%)	9 (25.0%)
Wicketkeeper	15 (9.9%)	4 (11.1%)
Bowler / All-rounder	98 (64.5%)	23 (63.9%)
Time Since Retirement		N=34
Mean (SD)	25.1 (13.9)	23.9 (12.1)
Range	2 - 57	4 - 50

5.3.1.2 Treatment of Wicketkeepers

A sensitivity analysis did not find a significant difference between exclusion of wicketkeepers and inclusion of wicketkeepers as "batsmen" for analyses including playing position. Therefore, wicketkeepers were categorised as "batsmen" to increase the power of results.

5.3.1.3 Association of Cricket-Related Variables

Functionally dominant side was not independent of playing position because playing position was used to determine functionally dominant side. Therefore, functionally dominant side was significantly associated with playing position ($p<0.001$). No other variables were significantly associated. Playing position and functionally dominant side were not included in the same model, so the collinearity assumption of logistic regression was still met for this study.

5.3.2 Prevalence

At the joint-level, the prevalence and 95% confidence intervals of joint-specific injury, cricket-related injury, NHANES pain, GP-OA, and joint replacement are shown in Tables 5.2 and 5.3. Knee injuries were most prevalent at 42.8%, closely followed by injuries to the spine at 40.1%, hand at 35.1%, and shoulder at 34.9%. Cricket-related injuries were most prevalent in the spine at 36.2%, with hand, knee, and shoulder cricket-related injuries having prevalences of 34.4%, 32.9%, and 27.6%, respectively. NHANES pain was also most prevalent in the spine at 39.5%, though GP-OA in the spine was only 7.2%. NHANES pain in the knee was reported by 30.9% of participants, and knee GP-OA and TKR had reported prevalences of 29.6% and 4.6%, respectively.

Table 5.2. Prevalence and 95% confidence intervals for joint-specific injury and cricket-related injury.

Joint site	Injury	Cricket-related Injury
Hip	17.8% (12.4 - 24.7%)	15.1% (10.2 - 21.8%)
Knee	42.8% (35.1 - 50.8%)	32.9% (25.8 - 40.8%)
Ankle	19.1% (13.5 - 26.2%)	13.8% (9.1 - 20.3%)
Spine	40.1% (32.6 - 48.2%)	36.2% (28.9 - 44.2%)
Shoulder	34.9% (27.6 - 42.9%)	27.6% (21.0 - 35.4%)
Elbow	11.3% (7.1 - 17.6%)	5.3% (2.7 - 10.3%)
Wrist	9.9% (6.0 - 15.9%)	6.6% (3.6 - 11.9%)
Hand	35.1% (27.8 - 43.1%)	34.4% (27.2 - 42.4%)

Table 5.3. Prevalence and 95% confidence intervals for joint-specific NHANES pain, GP-OA, and joint replacement.

Joint site	NHANES Pain	GP-diagnosed OA	Joint replacement
Hip	13.2% (8.6 - 19.6%)	11.8% (7.6 - 18.1%)	6.6% (3.6 - 11.9%)
Knee	30.9% (24.0 - 28.7%)	29.6% (22.8 - 37.4%)	4.6% (2.2 - 9.4%)
Ankle	5.9% (3.1 - 11.1%)	5.3% (2.6 - 10.2%)	--
Spine	39.5% (31.9 - 47.5%)	7.2% (4.0 - 12.7%)	--
Shoulder	23.7% (17.5 - 31.2%)	7.9% (4.5 - 13.5%)	--
Elbow	8.6% (5.0 - 14.3%)	--	--
Wrist	3.3% (1.4 - 7.7%)	1.3% (0.3 - 5.2%)	--
Hand	21.1% (15.2 - 28.3%)	2.6% (1.0 - 6.9%)	--

The prevalence and 95% confidence intervals of side-specific, joint-specific injury is shown in Figure 5.2. This reflects any injury resulting in 4 weeks or more of reduced

participation in exercise, training, or sport, whether or not the injury was cricket-related. Injuries were most prevalent in the spine at 40.1%; side-specific injuries were most prevalent in the left and right knees at 28.9%, followed by the right hand and right shoulder at 26.5% and 25.7%, respectively.

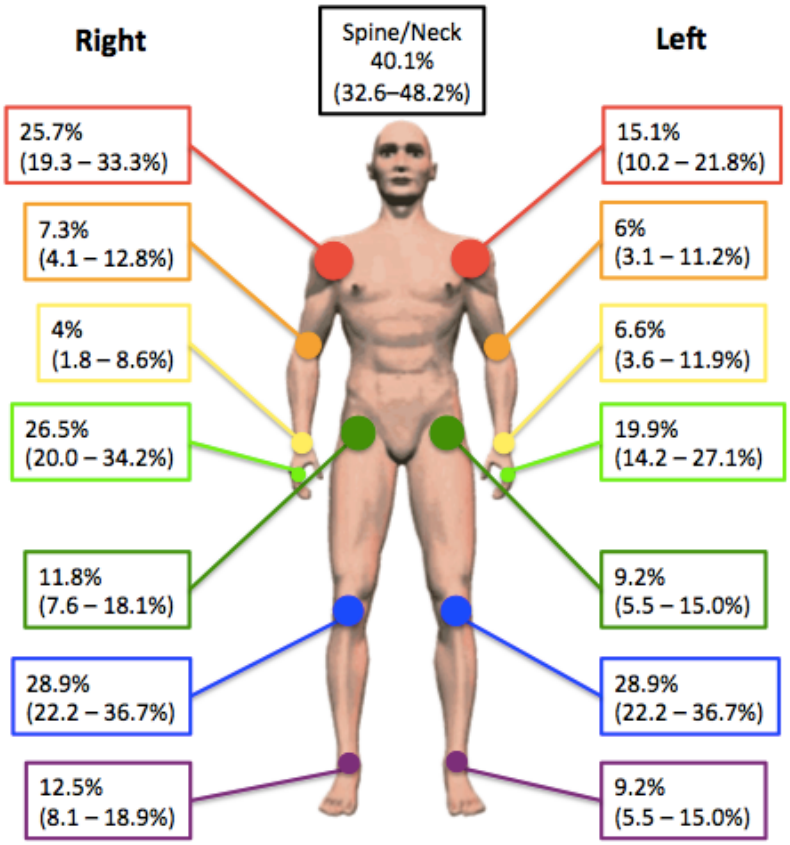


Figure 5.2. Prevalence and 95% CI for side-specific, joint-specific injury.

Figure 5.2 does not represent mutually exclusive injuries; one cricketer may have reported an injury to both knees and shoulders, or may have only reported a neck injury. To add clarity to the injury prevalence, the histogram in Figure 5.3 shows the number of joints that participants reported having experienced a severe injury (at the joint-level; not side-specific). Most participants only reported a severe injury in one joint; 12 participants reported severe injuries to five or more joints.

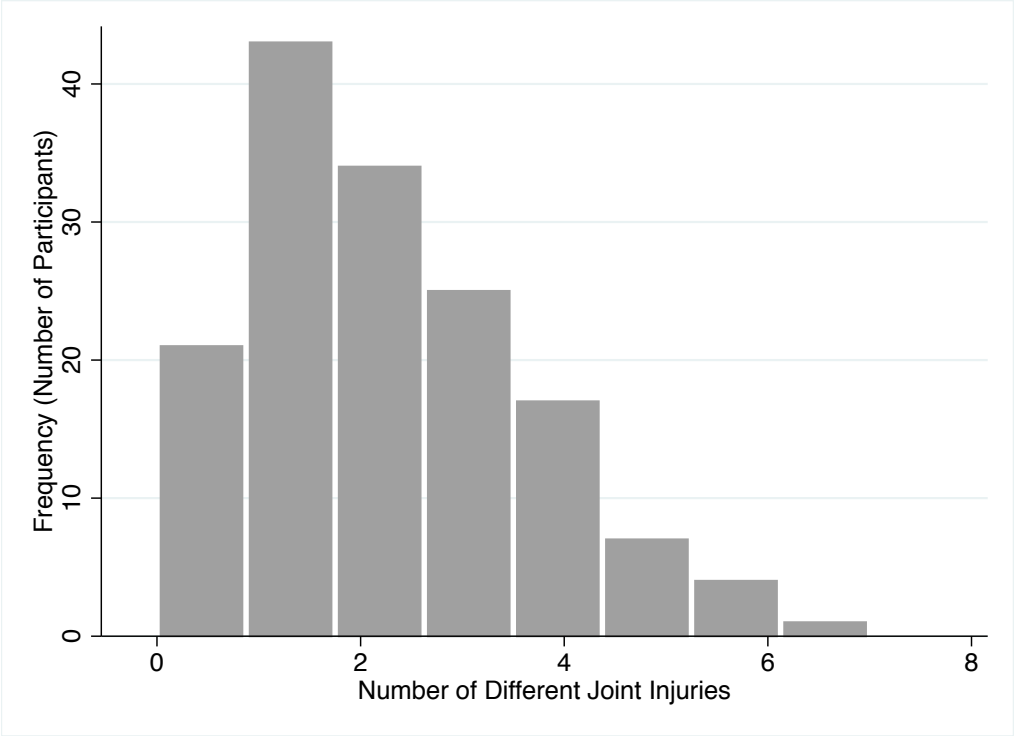


Figure 5.3. Frequency of number of joints reported by participants that experienced a severe injury.

Side-specific data for cricket-related injuries were not collected. However, by inspecting the number of injuries on a joint-level rather than a side-level, the majority of injuries reported were cricket-related for each joint. Both cricket-related injury and any reported injury have been described here to allow for joint-level and side-level analyses.

The prevalence and 95% confidence intervals of self-reported side-specific, joint-specific NHANES pain, GP-OA, and joint replacement are shown in Figures 5.4, 5.5, and 5.6. Side-specific pain was most prevalent in the left and right knees at 23.7% and 21.7%, respectively, and in the right shoulder at 17.9%. Side-specific GP-OA was most common in the left and right knees at 21.7% and 23%, respectively, and in the left hip at 8.6%. Joint replacements were only reported in the hips and knees and were most prevalent in the right hip at 5.3%.

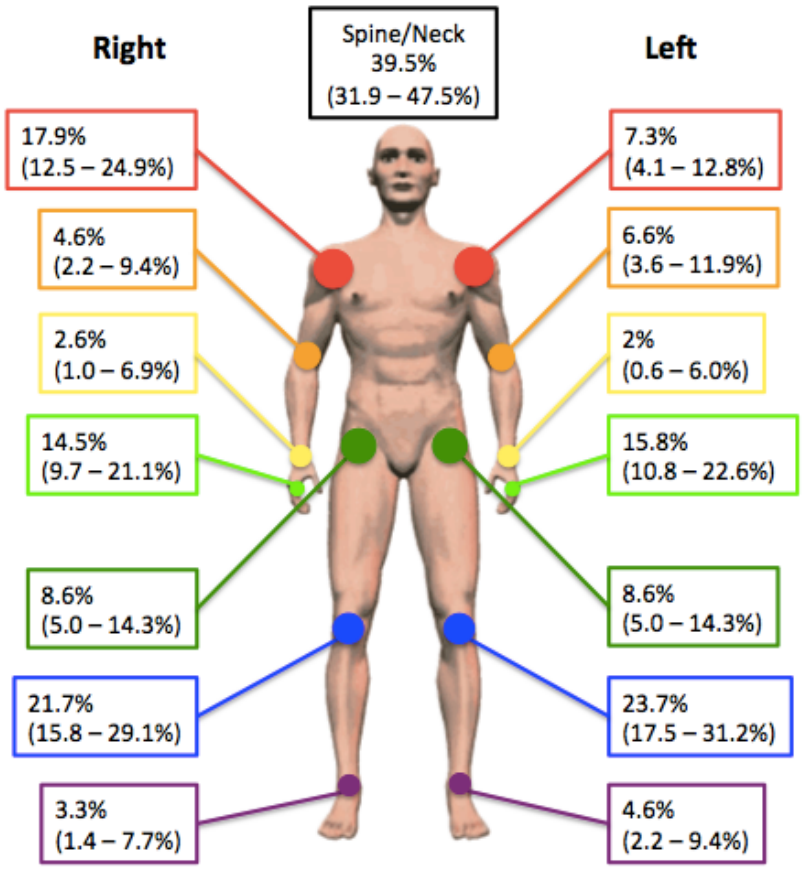


Figure 5.4. Prevalences and 95% CI for self-reported side-specific, joint-specific NHANES pain at the shoulder, elbow, wrist, hand, hip, knee, and ankle.

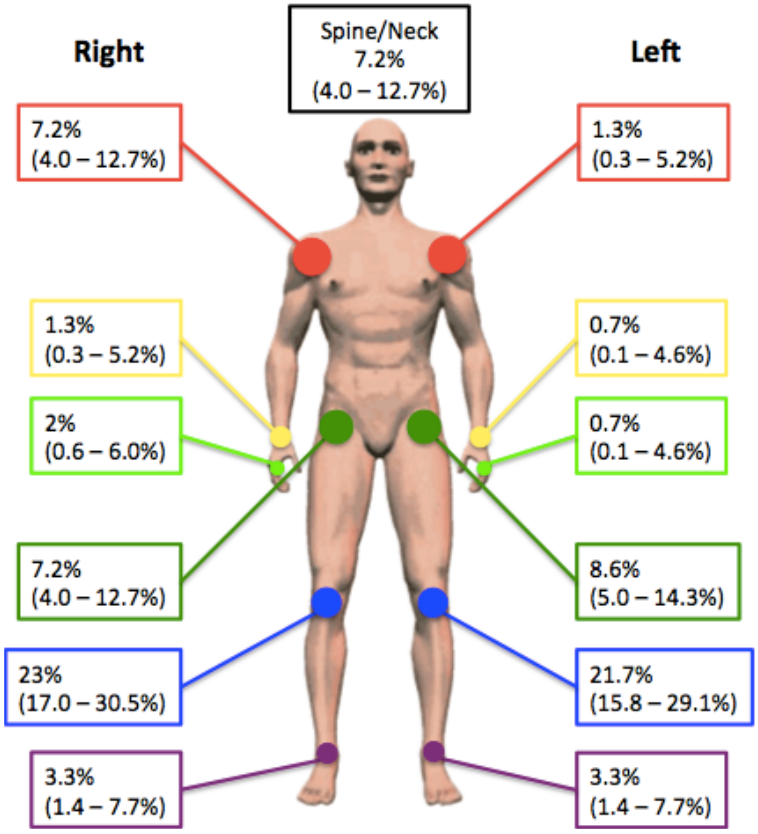


Figure 5.5. Prevalences and 95% CI for self-reported side-specific, joint-specific GP-OA at the shoulder, wrist, hand, hip, knee, and ankle.

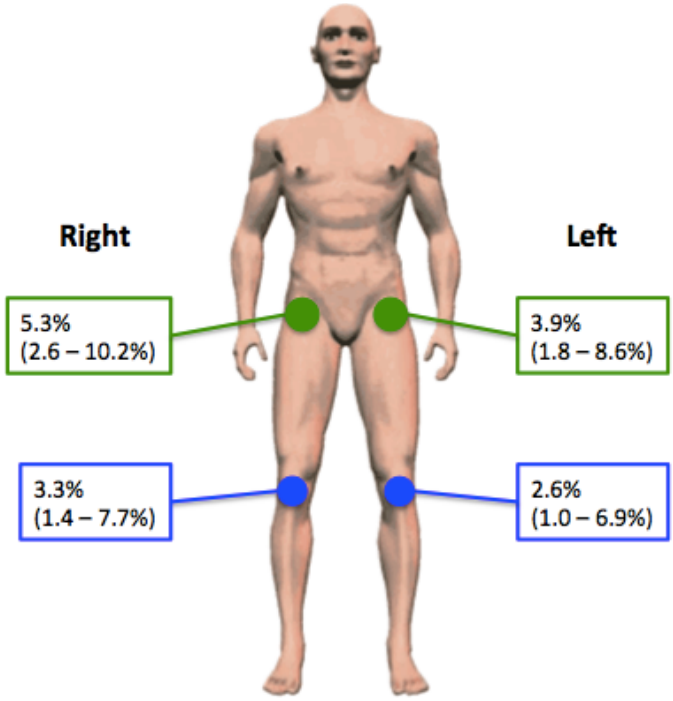


Figure 5.6. Prevalences and 95% CI for self-reported side-specific, joint-specific joint replacement at the hip and knee.

NHANES pain was most prevalent in the spine, knees, hands, and right shoulder. GP-OA was most prevalent in the knees, but also relatively more prevalent in the hips, spine, and right shoulder. Joint replacement was only reported for the hip and knee, and was most prevalent in the right hip.

5.3.3 Sensitivity and Specificity of OA Outcomes

The sensitivity and specificity for joint-specific NHANES pain to identify GP-OA and for GP-OA to identify joint replacement are shown in Table 5.4.

Table 5.4. Sensitivity and specificity for NHANES pain to identify GP-OA and for GP-OA to identify TJR.

NHANES to identify GP-OA	Sensitivity	Specificity
Hip	0.33	0.90
Knee	0.69	0.85
Ankle	0.50	0.97
Spine	0.64	0.62
Shoulder	0.58	0.79
Wrist	1.00	0.98
Hand	1.00	0.81
GP-OA to identify TJR		
Hip	1.00	0.94
Knee	0.86	0.73

The sensitivity and specificity analysis shows that in this population, NHANES pain was a good indicator of GP-OA for the knee, spine, wrist and hand. Though the sensitivity for NHANES pain in the hip, ankle, and shoulder was low, the specificity was high across all of the joints. The sensitivity and specificity in GP-OA to identify those with and without a joint replacement is high, suggesting that GP-OA is a good indicator of TJR. Figure 5.7 displays a Venn diagram of how these outcomes overlap for the hip.

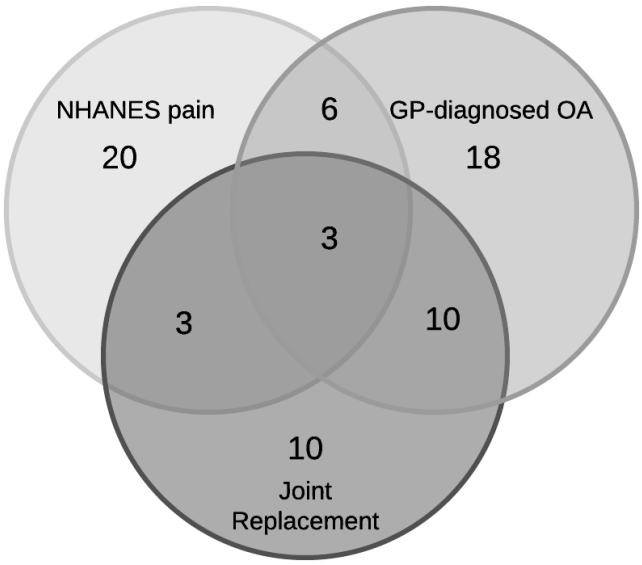


Figure 5.7. Venn diagram of the three joint outcomes described in this analysis, with frequencies for the hip.

Any one of the described outcomes is undesirable in a patient, which is why a positive response to any of NHANES pain, GP-OA, or TJR at a joint was used to define a poor joint outcome in the following analyses.

5.3.4 Multivariate Logistic Regression

Logistic regression was used to model the association of joint-level injury, cricket-related injury, number of professional seasons, and playing position with a poor joint outcome (any one of NHANES pain, GP-OA, or joint replacement at a joint). All models were adjusted for age and BMI, and number of professional seasons and playing position were adjusted for age, BMI, and injury. The odds ratios resulting from these logistic regression models are in Tables 5.5 and 5.6. Models with five or fewer cases were not reported, due to the instability of the model.

Table 5.5. Odds ratios and 95% confidence intervals for the association of each exposure with a poor joint outcome for the spine and lower limbs. Batsmen were the control for playing position, and functionally dominant side was the control for the dominant side analysis of bowlers.

Exposure	Poor Hip Outcome	Poor Knee Outcome	Poor Ankle Outcome	Poor Spine/Neck Outcome
Severe joint injury	1.56 (0.57 - 4.30)	6.92 (3.31 - 14.46)	8.65 (2.52 - 29.61)	2.19 (1.11 - 4.34)
Cricket-related injury	1.43 (0.50 - 4.06)	9.05 (3.95 - 20.74)	7.23 (2.11 - 24.80)	2.79 (1.38 - 5.62)
Number of pro seasons	1.00 (0.95 - 1.05)	0.98 (0.94 - 1.03)	0.96 (0.89 - 1.05)	1.02 (0.98 - 1.06)
Playing position*	0.84 (0.37 - 1.92)	1.56 (0.71 - 3.41)	Unstable, <5 cases	1.28 (0.63 - 2.63)
Functionally dominant side (N=98)	0.26 (0.03 - 2.16)	0.96 (0.30 - 3.05)	Unstable, <5 cases	---

*Playing position divided into "bowlers" and "batsmen" ("batsmen" included "wicketkeepers" for increased sample size)

Table 5.6. Odds ratios and 95% confidence intervals for the association of each exposure with a poor joint outcome for the upper limbs. Batsmen were the control for playing position, and functionally dominant side was not analysed for the upper limbs.

Exposure	Poor Shoulder Outcome	Poor Elbow Outcome	Poor Wrist Outcome	Poor Hand Outcome
Severe joint injury	3.99 (1.86 - 8.55)	8.04 (2.20 - 29.47)	Unstable, <5 cases	1.75 (0.77 - 3.98)
Cricket-related injury	2.93 (1.35 - 6.38)	Unstable, <5 cases	Unstable, <5 cases	1.51 (0.66 - 3.44)
Number of pro seasons	0.99 (0.95 - 1.04)	1.07 (0.99 - 1.16)	1.04 (0.94 - 1.15)◆	1.01 (0.96 - 1.06)
Playing position*	1.38 (0.60 - 3.18)	Unstable, <5 cases	Unstable, <5 cases	0.82 (0.36 - 1.87)
Functionally dominant side (N=98)	---	---	---	---

*Playing position divided into "bowlers" and "batsmen" ("batsmen" included "wicketkeepers" for increased sample size)

◆Not adjusted for wrist injury due to perfect prediction of failure

The functionally dominant side was only analysed for self-reported bowlers (*N=98*) in the lower limb joints, and did not have a significant association with poor joint outcomes.

5.3.5 Generalised Estimating Equations

GEE were used to analyse side-specific, joint-specific injury and functionally dominant side with side-specific, joint-specific poor joint outcomes. The resulting odds ratios and 95% CIs are shown in Table 5.7. The spine was not reported here; the wrist was also not reported due to fewer than 5 cases reported, causing instability of the model.

Table 5.7. Odds ratios and 95% confidence intervals for the association of side-specific injury and functionally dominant side with a poor joint outcome.

Exposure	Poor Hip Outcome	Poor Knee Outcome	Poor Ankle Outcome	Poor Shoulder Outcome	Poor Elbow Outcome	Poor Hand Outcome
Severe joint injury	2.20 (0.85 - 5.70)	3.53 (1.97 - 6.34)	13.99 (4.58 - 42.72)	5.09 (2.51 - 10.31)	8.60 (1.72 - 43.09)	1.84 (0.97 - 3.48)
Functionally dominant side (N=98)	1.00 (0.52 - 1.92)	1.10 (0.75 - 1.60)	1.14 (0.53 - 2.44)	---	---	---

As with the joint-specific logistic regression model, injury was strongly associated with poor joint outcomes. The functionally dominant side was only analysed with GEE for bowlers (*N=98*), and again did not have a significant association with poor joint outcomes in the lower limb joints.

5.3.6 Post Hoc Analysis: Functionally Dominant Side

While the functionally dominant side of bowlers did not appear to have a significant association with poor joint outcomes, an investigation into the prevalence of injury, pain, and OA, in bowlers by functionally dominant side was completed post hoc. The prevalence of side-specific injury, pain, and OA in the hip, knee, and ankle were stratified by functionally dominant side, as shown in Figure 5.8.

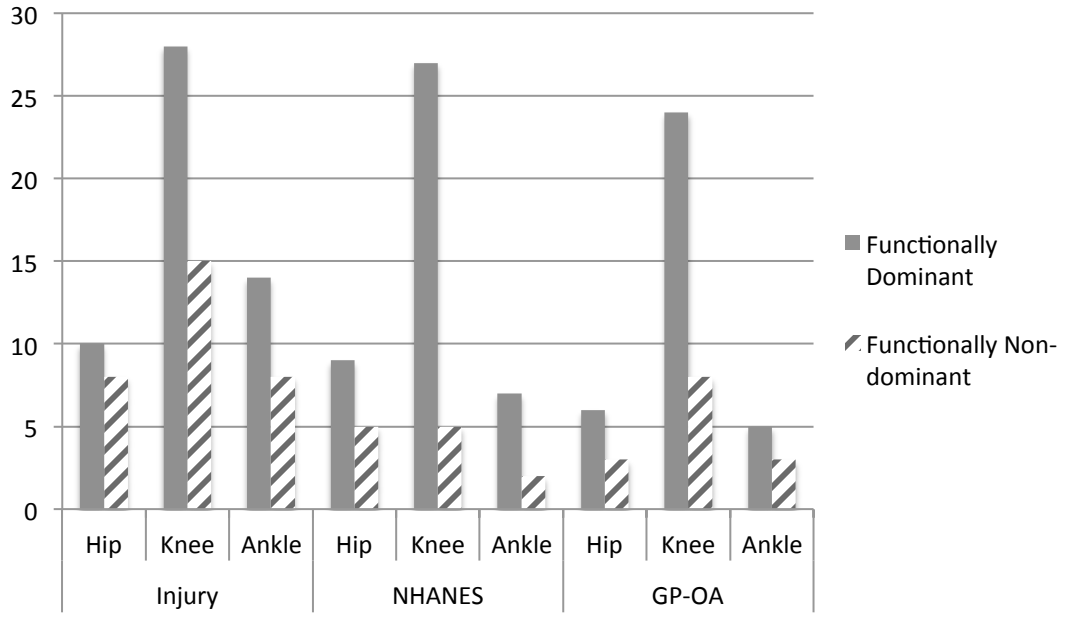


Figure 5.8. Proportion of bowlers with joint-specific outcomes (injury, NHANES pain, GP-OA) in their functionally dominant versus non-dominant lower limb.

The results of this post hoc analysis demonstrate that the side with the greater functional load during bowling had a greater proportion of injury, pain, and OA.

5.4 Discussion

This research is the first to explore the long-term musculoskeletal health and injury history of former elite cricketers across all joints and to investigate the relationship of cricket-related factors with long-term musculoskeletal outcomes. NHANES pain and GP-OA were highest in the knee. Higher prevalence of NHANES pain and GP-OA in the right shoulder compared to the left corresponded with the high proportion of right-armed bowlers. Injury, whether it was cricket-related or any severe joint-specific injury, had the most significant association with poor joint outcomes. Other cricket-related risk factors were not significantly associated with poor joint outcomes.

5.4.1 Sensitivity and Specificity Analysis

The specificity analysis indicated that a lack of NHANES pain identified participants that do not have GP-OA. The sensitivity indicated that those with NHANES pain may overestimate GP-OA in some joints, but clinician input advised that these participants may also include early OA that has not yet been diagnosed. The sensitivity and specificity of self-reported NHANES hip and knee pain calculated in this study are consistent with a previous study of self-reported pain validated with a clinical examination for OA (142). Ratzlaff et al found higher sensitivity for the hip than this study, but comparable sensitivity and specificity for the knee. The previous study pointed out that the critical criterion for use of self-reported measures in OA studies was the specificity, as a large number of false positives would cause "attenuation of the measure of association" (142). The specificity for NHANES pain across all joints in this

study was high, further justifying that it was appropriate to include a positive response of NHANES joint pain in classifying participants with a poor joint outcome.

5.4.2 OA rates relative to other sports

While joint-specific OA data is rare for joint sites other than the hip and knee, studies of lower limb OA in former elite athletes suggests that the prevalence in this population of retired cricketers is relatively low. Studies of former elite footballers have reported prevalences of knee OA ranging from 29% to 52% (69,143). Former elite Finnish athletes have a prevalence of knee OA up to 31% for weightlifters (69). Former elite Swedish athletes, none of which were cricketers, had prevalences of hip and knee OA of 14% and 15.5%, respectively (144,145). A Greek study of former elite athletes from various sports, none of which were cricket, reported clinical OA prevalences for the hip, knee, and ankle of 3.2%, 8.7%, and 3.6%, respectively (146). The mean ages of the former elite athletes in the previous studies ranged from 47 to 59; the former cricketers had a mean age of 57. Compared to the prevalence of hip, knee, and ankle OA in this study's population of 11.8%, 29.6%, and 5.3%, respectively, former cricketers are at the lower end of hip and knee OA prevalence among most former elite athletes.

Various previous studies, including the SMR analysis in the previous chapter, have suggested that elite athletes have an increased risk of OA compared to non-elite controls. The lower prevalence of OA in cricketers compared to other sports supports the idea that this risk is affected by the type of sport played (2,66).

5.4.3 Injury History

For both the joint-specific logistic regression model and the side-specific GEE, injury had the greatest association with poor joint outcomes. The logistic regression model for injury allowed for joint-specific comparison of odds ratios for injury with the other cricket-related exposure variables. The GEE model for injury allowed investigation of the

side-specific association of injury with side-specific poor joint outcomes. Significantly increased odds ratios for poor joint outcomes at the knee, ankle, shoulder, and elbow were seen in both models for injury. This is consistent with existing literature, showing a significant association between injury history and OA in former elite athletes (2,69,70).

Few previous studies examined the lifetime injury prevalence of former elite athletes. The study of former Australian Football League (AFL) athletes defined a serious injury as one resulting in admittance to hospital or surgery on the injured site. The study found that 57% of former AFL athletes had experienced a serious knee injury, 33% a serious ankle or foot injury, and 31% a serious shoulder injury (70). The prevalences for the cricketers were 43% for a serious knee injury, 19% for the ankle, and 35% for the shoulder. The threshold for a serious injury in the AFL study was higher than the threshold in this study of cricketers, so the prevalences in former AFL athletes would have been expected to be comparable to or less than that of cricketers. That the AFL athletes' prevalences were higher demonstrates a relatively low prevalence of lifetime injury history in this population of former elite cricketers.

A systematic review of the literature investigating the association between previous joint injury and subsequent OA determined that the combined estimated odds ratios were 3.8 (95% CI 2.0 – 7.2) at the knee and 5.0 (95% CI 1.4 – 18.2) at the hip (147). An odds ratio was not reported for previous injury and OA for any other joints. The studies contributing to this systematic review's odds ratios did not exclusively address sport-related injury. For previous injury and OA at the knee, the combined estimated odds ratio was lower than that of this study's odd ratio of 6.92 (95% CI 3.31 – 14.46). It is possible that the former cricketers experienced more severe knee injuries than participants in the reviewed articles, increasing the association between knee injury and subsequent knee OA. For the hip, this study's odds ratio was lower than that of the

systematic review but also non-significant, at 1.56 (95% CI 0.57 – 4.30). The review's odds ratio for the hip, though, included an odds ratio of 25 found in a study of Hong Kong Chinese participants, and may bias the combined estimated odds ratio at the hip. The non-significant odds ratio for hip injury and OA in the cricketers was consistent with a study of former professional football players (148).

The lack of side-specific cricket-related injuries may have impacted the effect size of cricket-related injuries in the person-level logistic regression models. For example, a cricketer may have had shoulder injuries in both shoulders but only right shoulder OA. Had side-specific cricket-related injury data been collected, this cricketer would have contributed equally to injury predicting OA, and injury not predicting OA. However, without side-specific data this cricketer will have only contributed to injury predicting OA, which would overestimate the association. Equally, the cricketer may have had cricket-related injuries to both shoulders and also had OA in both shoulders. In this case, the cricketer would have contributed doubly to injury predicting OA; however, without side-specific data this cricketer will have only contributed one case for injury predicting OA, which would underestimate the association. Therefore, the lack of side-specific cricket-related injury data may have impacted the effect size of cricket-related injuries in an unpredictable way. Evaluating this study's person-level and side-specific data for any severe injury demonstrates the unpredictable effect of side-specific data; at some joints, the side-specific effect size is greater than the person-level effect size, while at other joints the opposite is true. Future studies should ensure that side-specific, sport-related injury data is collected in order to clarify associations with side-specific outcome measures.

5.4.4 Playing load

No significant association was found between playing load, measured in number of professional seasons, and poor joint outcome, even when adjusted for joint-specific injury. This result is inconsistent with existing literature on the increased risk of injury and OA with increased number of games played by former AFL athletes (70). The lack of a significant association in the former cricketers between number of professional seasons and OA was unexpected, as an association would have followed from the hypothesis that increased loading contributes to OA in former elite athletes.

5.4.5 Playing Position

The lack of significant association between playing position and poor joint outcomes was also unexpected, given the difference in loading patterns for different playing positions. The prevalence of pain in the right shoulder was reported most by right-armed bowlers, but this did not translate into a significant association when adjusted for age and BMI. As mentioned in this chapter's introduction, fast bowlers tend to cover the most ground during a match and be more prone to injury than spin bowlers. It is possible that an association between playing position and poor joint outcomes was attenuated in bowlers due to the combination of spin bowlers and fast bowlers. The combination of spin and fast bowlers, though, was necessary for increased power of the results and stability of many of the regression models.

Further, it would have been expected that batsmen and wicketkeepers would have an association with knee outcomes, due to repeated squatting during play. The lack of association between playing position and poor joint outcomes in these cases may be due to a common training regime for cricketers and the necessity for all players to practice and perfect certain skills, like throwing. At the elite level, bowlers will spend more time

practicing bowling technique, but all batsmen will also be fielders that must practice throwing as well.

The insignificant association of playing position with poor joint outcomes in these cricketers may reveal a strength of the required variety of training for this sport. Further, many of these cricketers, regardless of playing position, will have played other sports during the winter, such as rugby. Other sports may account for some of their reported injuries, which may not have been as likely had their only sport participation been in their primary cricket playing position. The role of other sport participation cannot be ruled out, and may have attenuated any association of playing position with poor joint outcomes.

5.4.6 Functionally Dominant Side in Bowlers

Given the increased functional load and the high level of training completed by elite bowlers, the prevalence of poor joint outcomes would be expected to be higher in the leading leg. Though the functionally dominant side of bowlers was not significantly associated with poor joint outcomes in either the joint-specific logistic regression or the side-specific GEE models, post hoc analysis showed that the prevalences of injury, pain, and OA were higher in the functionally dominant side, or the leading leg. A bowler's leading leg tends to be contralateral to their dominant side, for example the side they would report if asked whether they were left- or right-handed. Population-based data has shown a significant relationship between handedness dominance and the side of hip OA and joint replacement. A study showed that, for example, a right-handed person was much more likely to receive a hip replacement in their right hip (149). The discrepancy of this study's results with the previous, population-based study may be explained by the differential in functional load seen during bowling. Such an explanation requires further

investigation into the structural and biomechanical differences between the functionally dominant and non-dominant legs of bowlers.

5.4.7 Limitations

The response rate of this cross-sectional study, as discussed in the previous chapter, was 13%, which raises concern about this sample's representativeness and generalizability. Selection bias from former cricketers with musculoskeletal issues was mitigated by advertising the study as one of "long-term health outcomes" rather than of "injury" or "joint health". Some selection bias, though, may have biased these results towards cases of former cricketers with musculoskeletal problems.

The sample size caused limitations in the number of variables that logistic regression models could adjust for. With a larger sample size, it would improve the strength of the results to adjust all of the models for at least age, BMI, injury, and smoking status, which are all known to be causally related to OA. Further, the low number of cases for some joint-specific outcomes caused the logistic regression model to be unstable, preventing reporting of a reliable odds ratio.

Injury histories were all self-reported and only recorded "severe" injuries, or injuries "resulting in 4 weeks or more of reduced participation in exercise, training, or sport". There may be some recall bias in whether or not all of a participant's serious injuries have been accounted for. There may also be some minor injuries that were not captured in this study's definition of a severe injury that contributed to a poor joint outcome. Recall bias and missing minor injuries may have underestimated the association of injury history with poor outcomes at some joints.

Side-specific cricket-related injury was not recorded. Instead, any severe joint-specific injury, cricket-related or not, was used to complete side-specific analysis. The side-

specific data on cricket-related injuries would be useful in determining the level to which the sport contributes to poor joint outcomes.

Playing position had to be altered from the categorization used in the previous chapter due to a lack of cases in some playing positions. Future studies of cricketers would benefit from an ability to differentiate between types of bowlers, batsmen, and wicketkeepers.

Playing load was measured in number of professional seasons, though this may not be the best metric for cricket-related load. A participant may not have played as much during their professional seasons as during seasons at a lower level, where they may have been relatively more elite. However, substantial recall bias would have been risked in choosing a different metric, such as number of games. While number of professional seasons may have underestimated the load in some participants, the aim was that this metric would be more reliable and would still capture time at which the participant was training at an elite level. A future study could validate participant responses with their published career data and establish a different metric for playing load.

5.5 Conclusions

This research is the first to explore the long-term musculoskeletal health and injury history of former elite cricketers. Poor joint outcomes were highest in the knees of former elite cricketers. Injury, whether it was a cricket-related or any severe joint-specific injury, had significant associations with poor joint outcomes at the knee, ankle, shoulder, and elbow. All other cricket-related risk factors were not significantly associated with poor joint outcomes. This research supports the hypothesis that the increased risk of OA seen in elite athletes is due to the increased risk of injury in elite sport, rather than the sport itself.

5.6 Disclosure of Publications Including Portions of This Work

Portions of this work, including the logistic regression results, have been submitted and accepted as a first author poster presentation to the OARSI World Congress 2017 (150).

Chapter 6 Methods: Current Elite Cricketer Study

6.1 Study Design and Aims

This chapter will describe the study design and methods used for the cross-sectional observational MRI and biomechanics studies in a convenient sample of current elite cricket fast bowlers. These studies addressed the third and fourth thesis objectives:

3. To assess the effect of elite fast bowling loads on knee cartilage volume in the higher loaded leading leg versus the trailing leg, as a potential mechanism for OA.
4. To test the sensitivity of cartilage to loading conditions by evaluating the associations of kinematic and kinetic parameters during the bowling action with knee cartilage volume.

This chapter will describe participant recruitment, ethics approval, protocol development for the MRI study, image analysis, biomechanics data collection, data cleaning, event identification, and statistical methods.

6.2 Participants: Current Elite Fast Bowlers

Participants were recruited from a convenient sample of fast bowlers, who were identified by the England Wales Cricket Board (ECB) as training and playing at an elite level and therefore invited to routine data collection days. Cricket fast bowlers were used due to the force differential between the leading and trailing legs during the bowling action; the leading leg experiences roughly twice the loading as the trailing leg (5).

6.3 Inclusion/Exclusion Criteria: Current Elite Fast Bowlers

All participants were aged 16 or above, did not have a condition that contraindicated an MRI, and did not have an injury that prevented them from completing biomechanics data collection. MRI analysis excluded participants without biomechanics data. All data were collected during routine data collection days conducted by the ECB at the end of the players' competitive seasons; the men's data were collected in 2015 and the women's data in 2016. The participant flowchart for the MRI and biomechanics studies is shown in Figure 6.1.

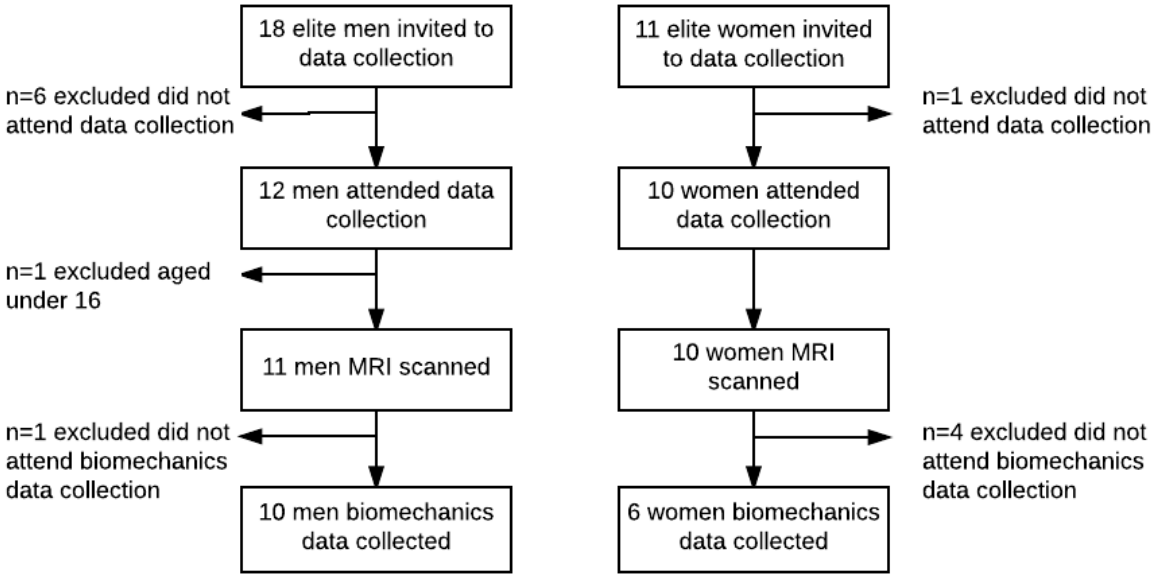


Figure 6.1. Participant flowchart for the current elite fast bowlers invited to the MRI and biomechanics studies.

Due to player availability, MRI scans were collected for eleven men and ten women; biomechanics data were collected for ten men and six women.

6.4 Ethics

The MRI study was given favourable opinion by the University of Oxford Central University Research Ethics Committee (MS-IDREC-C1-2015-189). The biomechanics data were routinely collected by the ECB and were anonymised to participant codes matched

to the MRI scan codes by an ECB researcher before being transferred for the purpose of this study.

6.5 Protocol Development: MRI study

The routine data collection conducted by the ECB includes lumbar spine MRI but not knee MRI. Therefore, a knee MRI protocol, including participant protocol, was developed for this study by the lead researcher (MEJ) with consultation from NHS radiographers. The use of MRI as the imaging medium for this study was selected for its enhanced resolution of cartilage structure when compared to the alternative of x-ray. While x-ray is a simple, validated medium to detect the cartilage structure surrogate measure of joint space, MRI has been used as a simple, reproducible method to provide quantitative information on cartilage volume (151).

6.5.1 MRI Scan Sequence

Potential MRI scan sequences are determined by the make and strength of the scanner used. The scanner available for this study was a 3.0-Tesla (3T) GE Discovery based at the National Centre for Sport and Exercise Medicine (NCSEM) at Loughborough University. Therefore, the scan sequence used for assessing cartilage morphology in this study was the sagittal 3D fast imaging employing steady-state acquisition with phase cycling (FIESTA-C) (TR/TE, 7.403ms/2.936ms; 1.0 mm section thickness; 14 cm field of view; 256 x 256 matrix; voxel size 0.18 mm x 0.18 mm), with standard radiofrequency (RF) coils while the participants were supine. The scan of each knee lasted 10 minutes.

The commonly recommended gold standard for cartilage morphology quantification is a water-excitation (or fat-supressed) T1-weighted spoiled gradient recalled echo acquisition in the steady state (SPGR) (152). However, a SPGR sequence was not available and several studies have found improved image quality in steady-state free

precession (SSFP) sequences such as FIESTA, compared to SPGR (153–155). Further, the Osteoarthritis Initiative (OAI) found that fat-suppressed, 3D dual-echo in steady state (DESS) provided the best universal cartilage discrimination for the knee (156). Therefore, the GE version of DESS and FIESTA-C scan sequences were tested on the 3.0T GE Discovery. While the DESS-equivalent sequence had clear delineation of bone from cartilage, the soft tissue delineation was less clear. The FIESTA-C scan sequence had clearer soft tissue delineation and so was deemed a more suitable sequence for the segmentation of cartilage at the knee.

6.5.2 Participant Protocol

A protocol was developed for the participants to obtain the most consistent scans of cartilage possible. Due to scheduling limitations, it was not possible to only scan in the morning and control for diurnal changes; a previous study has demonstrated that cartilage thickness decreases from morning to evening (157).

All participants were required to physically rest for a minimum of 45 minutes before knee scanning commenced in order to minimise load-induced deformation. The 45 minutes consisted of sitting for at least 20 minutes prior to scanning, during which time the consent form, safety questionnaire, and study-specific questionnaires were completed with the lead researcher (MEJ), and of laying supine for 25 minutes during routinely collected lumbar spine MRI scans prior to commencing the knee scans. These measures aimed to minimise the statistically significant, load-induced cartilage deformation that a previous study has shown in patellar cartilage volume (158). In a previous study of elite weightlifters and sprinters, participants were required to physically rest for 1 hour before scanning to minimize load-induced deformation (82). The present study was able to allow a minimum of 45 minutes of physical rest due to time restrictions for the MRI scanner.

6.5.2.1 Study-Specific Questionnaires

A questionnaire tailored for this study was used, instead of the retrospective questionnaire developed for the former cricketer study, in order to capture only those variables relevant to the aims of this study. All scanned participants completed two questionnaires (see Appendix C). The first was the validated Knee injury and Osteoarthritis Outcome Score (KOOS) to evaluate the following: Pain, other Symptoms, Function in daily living (ADL), Function in Sport and Recreation (Sport/Rec), and knee-related Quality of Life (QOL) (43). KOOS scores were collected as a descriptive metric for the cricketers' pain and function; KOOS has previously been used in studies of athletes (159,160). A score of 100 reflected no symptoms of pain or functional limitations, a score of 0 reflected extreme pain and functional limitations (43).

The second questionnaire was a sub-set of cricket-specific questions from the retrospective questionnaire and new questions relevant to this study. The continuous variables of age, years at an elite level, and average overs bowled per season as a professional were collected. The categorical variables of bowling arm, batting arm, and severe knee injury history (4 weeks or more of reduced participation in exercise, training or sport) were collected. The primary risk factor was the leading leg versus the trailing leg; the leading leg was defined as the leg contralateral to the bowling arm. The bowlers' age, years at an elite level, and average overs bowled per season as a professional were important to determining if the loading due to cricket bowling differed between the male and female bowlers. Severe knee injury was a potential confounder in the biomechanics study.

6.6 Image Analysis: MRI Study

MRI scans were analysed to determine knee cartilage volume in the leading and trailing legs. Due to the time-consuming nature of image analysis, the number of subjects

included in image analysis was restricted to participants with both MRI and biomechanics data available (ten male and six female bowlers).

6.6.1 Cartilage Volume Segmentation

The compartmental cartilage volumes were calculated for the two knees of each of the sixteen bowlers. The cartilage compartments analysed were the patella, medial tibia, and lateral tibia. Manual segmentation of compartmental cartilage volumes was performed on multiplanar reconstructed (MPR) images using 3D Slicer Version 4.4, an open source software. No previously published protocols were found for non-proprietary manual segmentation of cartilage at the knee, therefore a novel protocol was developed by the lead researcher (MEJ) in collaboration with a segmentation expert and with consultation from a musculoskeletal radiologist (see Appendix D for details of the complete protocol). The "WandEffect" and "DrawEffect" functions were used with a mouse to segment the cartilage into patellar, medial tibia, and lateral tibia compartments. Each compartment was given a distinct colour and was manually segmented on a slice-by-slice basis. The patellar cartilage was first segmented in the sagittal plane and then this segmentation was cleaned from the axial plane. The tibial cartilage was first segmented in the coronal plane and then cleaned in the sagittal plane, all on a slice-by-slice basis. The compartment volumes were then calculated within 3D Slicer by summing the voxels for each compartment and converting the voxels to cubic millimeters.

6.6.2 Normalisation of Medial and Lateral Tibial Cartilage Volume

The medial and lateral tibial cartilage volumes were normalised using the cross-sectional area of the medial and lateral tibial bone, respectively. The cross-sectional area measurement of tibial bone included the thickness of one voxel, giving the tibial bone measurements the units of cubic millimetres. This maintained the same units as the cartilage volume measurements, making the normalised cartilage measurements

unitless. It is recognized that for the tibial bone, the reported measurements are actually a volume; however, for language consistency with previous literature and for simplicity of explanations, the tibial bone measurements will be referred to as "areas".

Normalisation accounted for known differences in size between males and females, allowing for the male and female tibial compartment measurements to be combined and compared in a total bowler sample, and also accounted for overall body size differences between players of the same sex. The medial and lateral tibial bone areas were calculated according to the methods described in Ding et al: the bone areas of the medial and lateral tibial plateaus were measured from axial images at the bone surface of each plateau (161). The edges of the medial and lateral tibial areas were pinpointed as collinear with the apex of the medial or lateral tibial spines on the coronal slice at which the posterior cruciate ligament enthesis could be identified. These points were then triangulated on the axial slice to determine the edge of the medial and lateral bone areas. The medial and lateral tibial cartilage volumes were then divided by the respective compartmental cross-sectional bone area to acquire a normalised compartmental measurement.

6.6.3 Segmentation Reliability Studies

Two reliability studies, one of patellar cartilage and one of tibial cartilage, were completed to test the intra- and inter-observer reliability of the newly developed segmentation protocol.

Intra-observer reliability was tested for the patellar cartilage volume and for the tibial bone area. The patellar cartilage volume for five randomly selected knees was segmented and calculated twice by the lead researcher; three of these knees were segmented three times to account for a learning effect. The medial, lateral, and total tibial bone areas of three different, randomly selected knees were also segmented three times.

Inter-observer reliability was tested for the patellar cartilage volume. A medical student was trained using the newly developed segmentation protocol. The medical student had completed one undergraduate year in medicine and had no experience with segmentation or MRI. She was trained by the lead researcher (MEJ) and segmented and calculated the patellar cartilage volumes for four randomly selected female knees. These measurements were compared to those of the lead researcher for inter-observer reliability of patellar cartilage volume.

To quantify intra- and inter-observer reliability, both the root-mean-square coefficient of variation (RMSCoV) and the intra-class correlation coefficient (ICC) were reported. The RMSCoV was reported for the sake of comparison with other published reliability measures for cartilage segmentation (162,163). The RMSCoV was calculated using equation 4.1:

$$RMSCoV = \frac{\sqrt{\sum_{i=1}^{N} SD_i^2}}{\sqrt{\sum_{i=1}^{N} \mu_i^2}} \quad [4.1]$$

where *N* is the number of knees, SD is the standard deviation for each knee, and μ is the mean for each knee, consistent with previous literature (162). Duryea et al had an intra-observer RMSCoV range from 1.6 – 3.5% and an inter-observer RMSCoV range from 2.5 – 8.6% for its semi-automated knee cartilage segmentation method (162). Brem et al also used 3D Slicer software and had an intra-observer RMSCoV between 1.0 – 3.7% (163).

The ICC was reported to provide an index accounting for both degree of correlation and agreement between measurements. ICC estimates for both intra- and inter-observer reliability were calculated using Stata 14.2. The ICC for intra-observer reliability was based on a single rater, absolute agreement, 2-way mixed effects model; the ICC for inter-observer reliability was based on a mean of 2 raters, absolute agreement, 2-way

mixed effects model, consistent with published recommendations (164). Absolute agreement was used in order to account for any systemic bias in the measurements.

The formula for the ICC is shown in equation 4.2:

$$\frac{MS_R - MS_E}{MS_R + (k-1) * MS_E + \frac{k}{n} * (MS_C - MS_E)} \quad [4.2]$$

where MS_R is the mean square for rows, MS_W is the mean square for residual sources of variance, MS_E is the mean square for error, MS_C is the mean square for columns, n is the number of subjects, and k is the number of raters or measurements. Koo and Li suggest the following general guidelines when reporting and interpreting an ICC:

"Values less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability" (164).

Results from the reliability studies are discussed in Chapter 7.

6.7 Statistical Methods: MRI Study

This section describes the statistical methods used for the cross-sectional current elite bowler MRI study. A summary of statistical methods will also be included in relevant experimental chapters (Chapters 7 and 8).

6.7.1 Primary Analysis: Leading Leg Versus Trailing Leg Cartilage Volume Comparison

The compartmental cartilage volumes were compared for the leading versus the trailing leg in each player using a paired t-test. The cartilage volumes and normalised cartilage measurements from the leading and trailing legs of each player were paired observations that required a paired difference test. Visual inspection was used to test the normality of the cartilage volumes and ensure a parametric test was appropriate. Stata 14.2 was used to test normality and to determine whether to reject the null hypothesis

that the true mean difference between leading and trailing leg compartmental cartilage volumes was zero.

6.7.2 Secondary Analysis: Clinically Significant Difference

To investigate a clinically relevant measure, a secondary analysis calculated the percent differences for compartmental cartilage volumes and normalised tibial measurements between the leading and trailing legs. A study of 429 patients from the Progression Cohort of the Osteoarthritis Initiative (OAI) established minimal clinically important difference (MCID) of 6.6% for cartilage volume change at the knee in patients with OA, a threshold which was validated against radiographic OA progression (165). Normally used in longitudinal studies, the percent difference between cartilage volumes in both knees of each participant provided a cross-sectional and clinically relevant measure. The percent difference was calculated in Microsoft Excel based on the hypothesis that the leading leg measurements would be greater, and so assumed the trailing leg to be the initial value. This is shown in equation 4.3:

$$\%\ difference = \frac{(Leading - Trailing)}{Trailing} \times 100 \qquad [4.3]$$

6.8 Protocol: Biomechanics Study

The routine data collection by the ECB includes biomechanics during the bowling action. The biomechanics data were collected for the ten men on the same day as MRI scanning and for the six women five weeks after MRI scanning. The routine biomechanics data collection is described in this section.

6.8.1 Data Collection Equipment

Kinetic and kinematic data were collected using a Kistler force plate (1008 Hz, 900 x 600 mm, Type 9287B, Winterthur, Switzerland) and an 18 camera (MX13) Vicon Motion

Analysis System (Vicon Motion Systems, Oxford, UK) in the indoor nets at the ECB National Cricket Performance Centre (Loughborough, UK). The data collection frequency for the cameras was 300 Hz for both the male and female bowlers; the data collection frequency for the force plate was 300 Hz for the men and 1800 Hz for the women.

6.8.2 Camera Error Assessment

The error of the cameras was measured prior to beginning each day's data collection. This was accomplished by running a trial of a calibration wand within the data collection volume. The calibration wand was shaped like a "T", with two markers placed a known 240mm apart. The trace of the distance between these calibration wand markers was plotted to assess the error in the distance measurement and tended to vary within about 0.20mm of the known 240mm distance.

6.8.3 Marker Set

A trained physiotherapist placed the forty-four 14 mm retro-reflective markers on bony landmarks of each bowler using a sports adhesive spray and double-sided tape, and reflective duct tape was put on the cricket ball to create a ball marker. The position of the markers was in accordance with previous bowling studies performed by the ECB Biomechanics team (166). Markers were placed in the following positions: front of head left and right (2), back of head left and right (2), C7/cervical spine (1), thoracic spine (1), lumbar spine (1), clavicle (1), sternum (1), anterior and posterior shoulder left and right (4), shoulder left and right (on top of the clavicle nearest the acromioclavicular joint) (2), back (on the scapula of the bowling arm) (1), lateral and medial elbow left and right (4), radial and ulnar bony landmarks of the wrist left and right (4), left and right hand (placed on the third metacarpal) (2), anterior and posterior superior iliac spine left and right (4), medial and lateral knee left and right (4), medial and lateral ankle left and right

(4), heel (1), toe (on the second metatarsal) (1), medial and lateral toes left and right (on the first and fourth metatarsals) (4). A bespoke back marker set was placed on the female bowlers for a separate study, but only three markers from the back marker set were used in this analysis: one for the C7/cervical spine, one for the thoracic spine, one for the lumbar spine. An example of the marker set is shown in Figure 6.2.

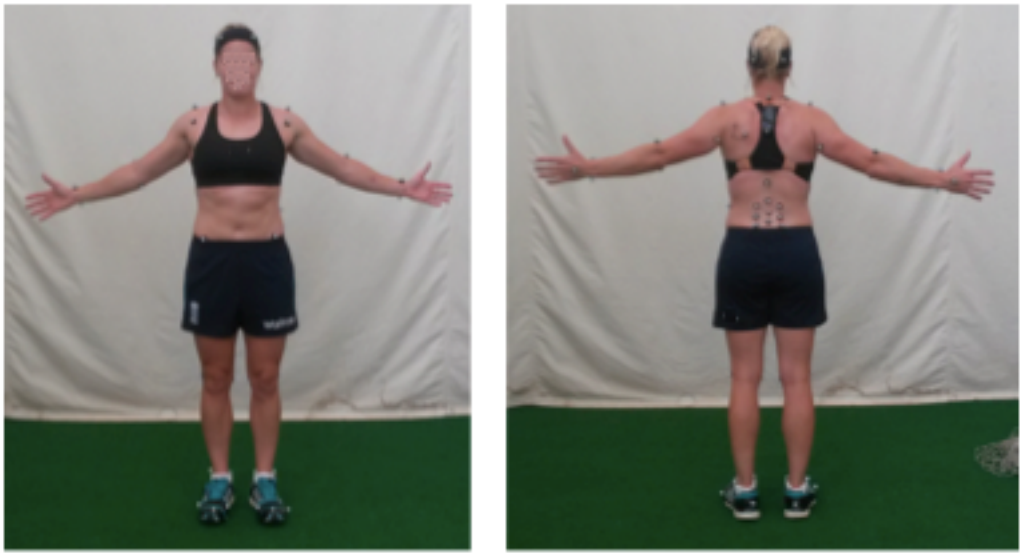


Figure 6.2. Example of the placement of the 45 markers used (only three markers were used in analysis from the lower back marker set: one for the C7/cervical spine, one for the thoracic spine, one for the lumbar spine).

6.8.4 Data Collection

Multiple bowling trials were collected for each player in order to collect a clean foot plant on the force plate, meaning that the entire foot landed on the force plate. The force plate was disguised among the flooring of the indoor nets. These nets are regularly used by these athletes for indoor training, and so provided as natural an environment as possible for data collection.

The ball speed and type of bowl were also collected during each bowling trial. Only stock or maximum effort bowls were considered for analysis.

6.9 Data Cleaning: Biomechanics Study

Nexus 1.7.1 was used to process the Vicon data collected for the male bowlers, and Nexus 1.8.1 (Vicon Motion Systems, Oxford, UK) was used for the female bowlers. The trials analysed were chosen based firstly on a clean foot strike on the force plate, secondly on the bowl with the fastest ball speed during regular or maximum effort bowls. One trial for each bowler was cleaned and used for analysis; this section describes how the chosen trials were cleaned.

6.9.1 The Delivery Stride

The bowling action consists of the run-up, pre-delivery stride, delivery stride, and follow-through (5). Only the delivery stride of the bowling action was cleaned for this study. The delivery stride was of interest because it contains the steps with the greatest forces during the bowling action. The delivery stride is defined as the motion between trailing foot strike and ball release. Trailing foot strike occurs at the end of the player's run-up, after the pre-delivery stride; ball release occurs after leading foot strike. Figure 6.3 shows a sample from the Vicon data of trailing foot strike, leading foot strike, and ball release. For each trial, the forty-five markers and the ball marker were labelled for 20 frames before trailing foot strike and for 20 frames after leading foot toe off in order to capture the entire delivery stride.

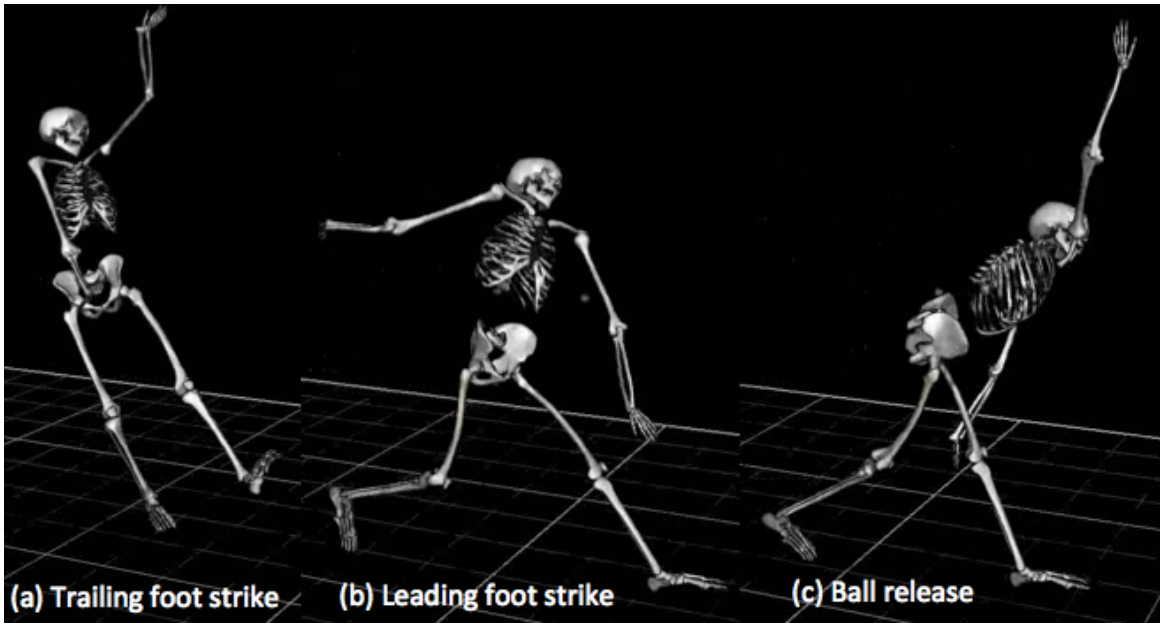


Figure 6.3. Sample image of the delivery stride: (a) trailing foot strike, (b) leading foot strike, and (c) ball release, from one participant's Vicon data.

6.9.2 Gap Filling

Gaps occur in the kinematic data when none of the cameras capture the position of a marker in a frame. Gaps of 3 or fewer frames were filled using a spline fill. Gaps of 4 or more frames were filled using Vicon's "copy trajectory" function. The copy trajectory function used a reference marker with a similar trajectory to the marker with a gap, in order to predict the trajectory of a marker through a gap. All gap-filling trajectories were visually inspected to ensure reasonable values were estimated.

When marker sets were complete and labelled, processed kinetic and kinematic data were exported to Excel files for further cleaning and analysis.

6.10 Event Identification: Biomechanics Study

The methods for this study's event identification were developed by the lead researcher (MEJ). The key events identified during the delivery stride were trailing foot strike, leading foot strike, and ball release. Data from cleaned Vicon trials were imported to MATLAB R2014b (MathWorks, Natick, MA, USA) for event identification. For all participants, at least one trial analysed was for the leading foot strike on the force plate.

For some participants, a second trial was analysed for the trailing foot strike on the force plate. Not all bowlers had a trial with a clean trailing foot strike on the force plate, due to time constraints during data collection.

6.10.1 Trailing Foot Strike

Trailing foot strike was defined differently by the lead researcher (MEJ) for the men versus the women, due to different pre-delivery stride techniques. The women's pre-delivery stride was similar to a normal step in their run-up; the men's pre-delivery stride acted as more of a preparation step that slowed and collected their approach into the delivery stride. For the women, trailing foot strike was defined as the frame at which the velocity of the centre of the foot (the midpoint between the lateral ankle marker and toe marker) reached a negative maximum, as shown in Figure 6.4.

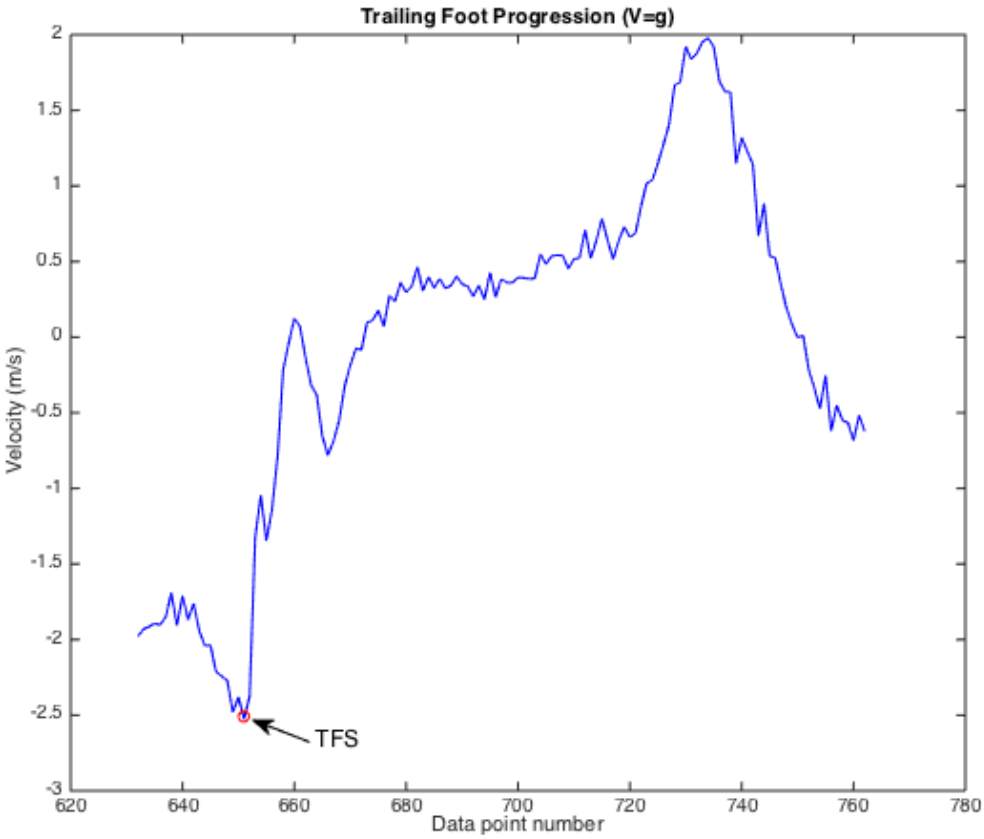


Figure 6.4. Trailing foot strike identification for female bowlers: Velocity of the trailing foot centre, with trailing foot strike indicated with "TFS" at the velocity's negative maximum.

For the women, this point corresponded to the frame at which the foot contacted the ground, causing the foot velocity to stop becoming more negative. This point from the marker data was validated with the force plate data; the frame estimated by the foot velocity predicted the frame of force plate contact within 1 to 2 frames, before the force plate registered contact. The frame estimated by the foot velocity was also visually validated using the Nexus software to compare the visually-determined frame of foot contact, and was within 1 frame of the visually-determined foot contact. This validation showed that the foot centre velocity definition for trailing foot contact reliably captured the actual trailing foot strike.

For the men, the negative maximum of the foot centre velocity did not accurately capture trailing foot strike. Many of the male fast bowlers appear to brace themselves during the pre-delivery stride as they approach trailing foot strike, causing the foot centre to have a relatively constant velocity before hitting the ground. Therefore, trailing foot strike was defined as the frame before the slope of the trailing foot centre's velocity reached a maximum, as shown in Figure 6.5.

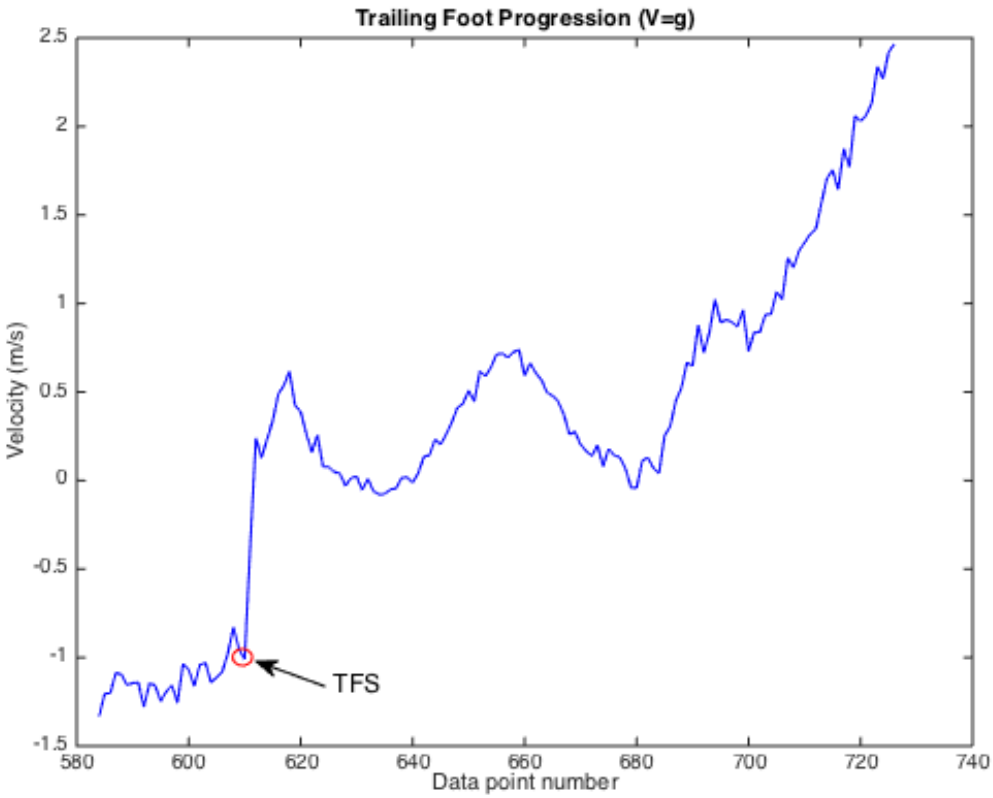


Figure 6.5. Trailing foot strike identification for male bowlers: Velocity of the trailing foot centre, with trailing foot strike indicated with "TFS" at the frame before the velocity's slope reached a maximum.

For the men, this point was assumed to be the point at which the trailing foot hit the ground, causing the foot centre to rapidly decelerate towards zero velocity. Force plate data was not available for trailing foot strike for most of the men due to time constraints during data collection, so Nexus software was used to visually validate the trailing foot strike frame. Using Nexus, the maximum deceleration estimate of trailing foot strike was found to be within 1 frame of trailing foot contact, as visually-determined by inspecting the heel and toe markers frame-by-frame. This validation showed that the foot centre deceleration estimate for trailing foot contact reliably captured the actual trailing foot strike.

6.10.2 Leading Foot Strike

Leading foot strike was defined by the lead researcher (MEJ) the same for male and female bowlers using force plate data. Leading foot strike was defined as the frame at

which the z-direction force became greater than an experimentally determined noise threshold, as shown in Figure 6.6. The noise threshold was determined to be 200 N for this sample of bowlers; thresholds greater than this threshold significantly changed the frame of leading foot strike for some bowlers. Leading foot strike was visually validated with Vicon data. This validation showed that the frame at which z-direction force went beyond a 200 N noise threshold reliably captured the actual leading foot contact.

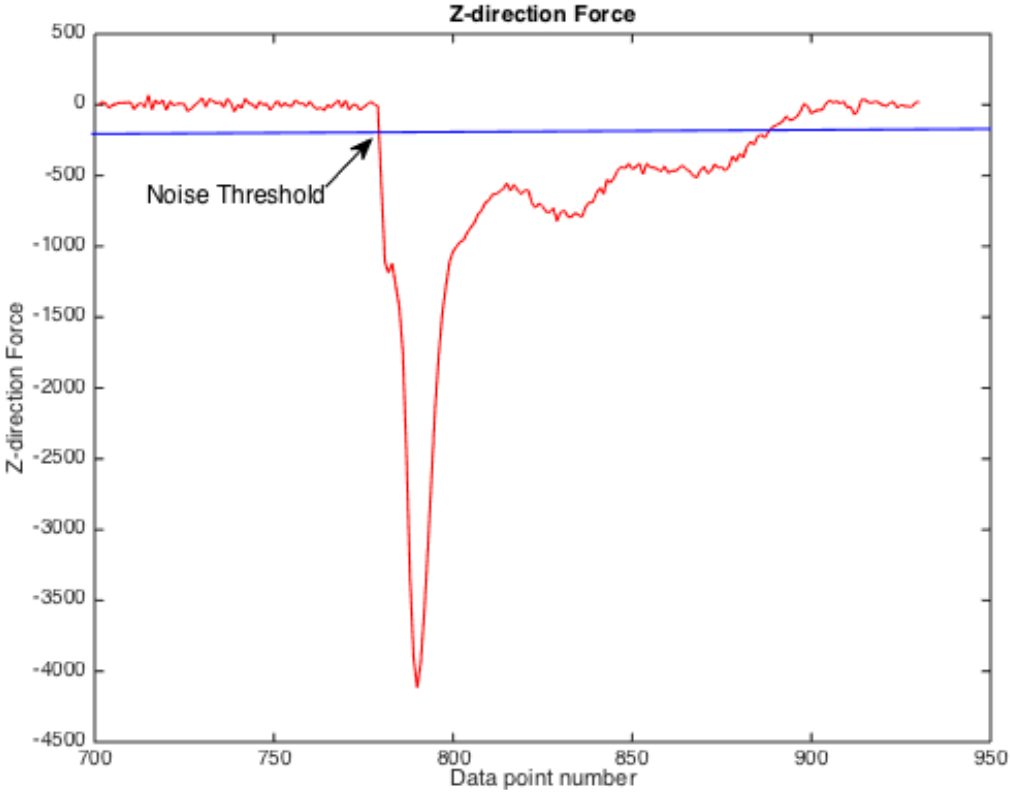


Figure 6.6. Leading foot z-direction force trace, with noise threshold marked with a horizontal blue line.

6.10.3 Ball Release

Ball release was defined as the frame at which the distance between the ball marker and the radial wrist marker became greater than 20mm, consistent with previous bowling literature (167). A sample of this distance over time relationship from this study is shown in Figure 6.7.

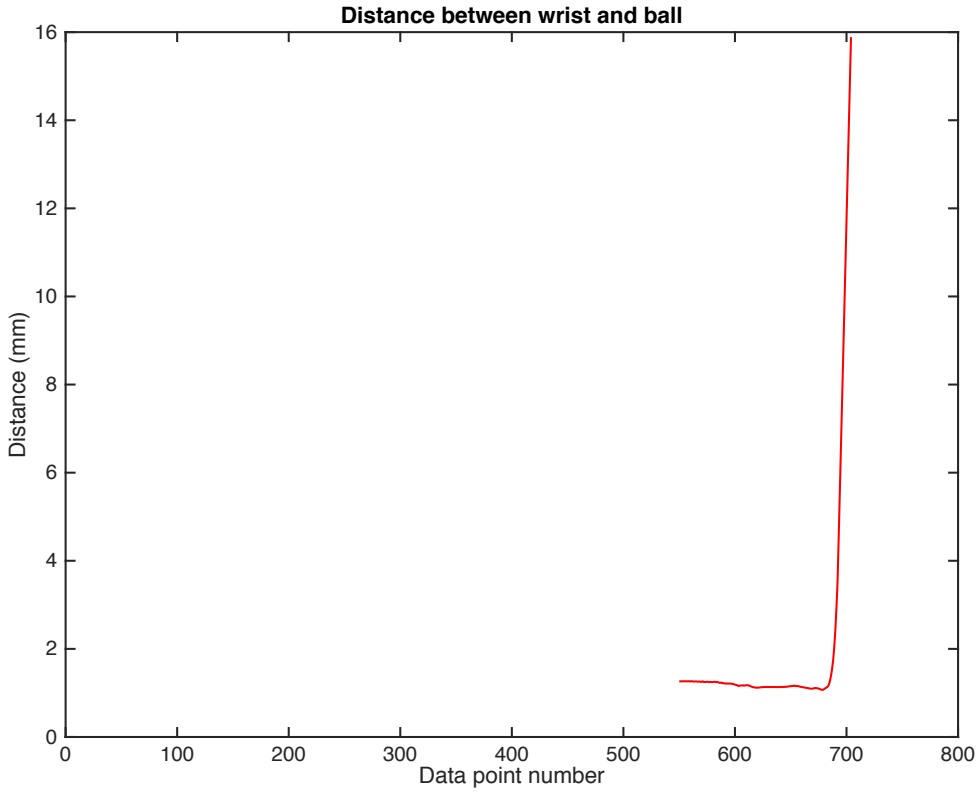


Figure 6.7. Trace of the distance between the radial wrist marker and the ball marker, to demonstrate ball release.

After identification of these key events, the marker data during the delivery stride was standardised for all bowlers from zero to one hundred percent (5). This standardisation allowed for the comparison of kinematic metrics between bowlers, even if bowlers took a different amount of time to go through the delivery stride.

6.10.4 Repeatability of the Bowling Action

The bowling action is assumed to be a repeatable action for this study. The centre of mass (COM) speed was evaluated to test this, with the assumption being that COM speed would remain the same between bowls in controlled experimental conditions. The COM was estimated as the midpoint of the right and left anterior superior iliac spines. The maximum speed of the COM was calculated for bowlers with multiple cleaned trials, which included five female bowlers. A paired t-test was used to determine if the maximum speed during the delivery stride was statistically significantly different. The

COM speed trace showed consistent trends between trials and the paired t-test for maximum COM speed found no statistical difference between repeated bowling actions ($p=0.39$). This quantifies one aspect of the assumption that the bowling action is repeatable.

6.11 Knee Parameter Calculation: Biomechanics Study

The kinetic and kinematic parameters required for analyses were leading knee angle at leading leg strike and leading knee moment at leading leg strike. This section describes how these parameters were calculated.

6.11.1 Plug-In Gait (PIG) Model

For the ease and efficiency of calculating the knee kinetics and kinematics, it was desirable to apply the Plug-In Gait (PIG) model to the bowlers' Vicon marker data and force plate data. The PIG model is Vicon's validated and widely used implementation of the conventional gait model. The PIG model estimates the position and orientation of body segments on a frame-by-frame basis using a specific marker set, the participant's weight and a few key anthropometric measurements (168–178)

PIG calculates knee moments in the local tibia coordinate frame by solving the equations of motion for the segments of the lower limb (foot, shank, thigh) according to Kadaba et al (173). This is done using the external forces applied to limbs provided by a force plate, estimates of the distribution of mass in the limb segments according to Winter et al (178), and the kinematics of the limb segments (179).

PIG relies on the accurate placement of markers and requires 3 or more markers for each segment. For the estimation of the position and orientation of the knee, markers on the thigh and tibia are required. However, the marker set used for the bowlers was designed for ECB bowling motion capture analysis and did not have the thigh and tibia markers.

Therefore, these missing markers were estimated to allow use of the PIG model. The thigh marker was estimated as the mean of the x, y, and z components of the lateral knee and anterior superior iliac spine markers and the tibia marker was estimated as the mean of the x, y, and z components of the lateral ankle and lateral knee markers.

Other models of the knee, particularly the Grood and Suntay (G&S) convention, did not require additional, estimated markers (180). To ensure the accuracy of the outputs of the PIG model based on estimates of the thigh and tibia markers, the knee angles during the delivery stride were calculated using the G&S convention and compared to those calculated by the PIG model.

6.11.2 Knee Kinematics

MATLAB was used in order to calculate the knee kinematics with the G&S convention. This convention utilises anthropometric measurements and markers from the pelvis, knee, and ankle to calculate embedded, or local, femoral and tibial coordinate systems that are used to calculate knee angles.

6.11.2.1 Embedded Coordinate Systems

Embedded coordinate systems are generated for the tibia and femur in order to calculate angles between these coordinate systems. Embedded coordinate systems allow accurate angle calculation even if the participant moves outside of one plane. Using global coordinates, or the position of markers directly from motion capture analysis, for knee angle calculation would assume that the participant moves only in one plane. For example, using global coordinates to calculate knee flexion angle would not account for slight abduction of the foot during flexion, and so could miscalculate the knee flexion angle.

6.11.2.2 Joint Centre Calculation

To generate embedded coordinate systems in the tibia and femur, the joint centres for the hip, knee, and ankle were first determined. The hip joint centres were estimated

using the Harrington method; this method was chosen because it has been validated using MRI and it is widely used in gait analysis (181). The Harrington method uses regression equations and anthropometric measurements of the pelvis and leg to calculate the hip joint centre relative to a local pelvic coordinate system. A translation and rotation matrix was applied to the hip joint centres in order to translate them into global coordinates. The hip joint centre is translated to global coordinates so that it can be used with the knee joint centre and knee markers in establishing a local femoral coordinate system.

The knee joint centre was estimated as the midpoint of the medial and lateral markers on each knee, in global coordinates. Similarly, the ankle joint centre was estimated as the midpoint of the medial and lateral markers on each ankle.

6.11.2.3 Femoral and Tibial Embedded Coordinate Systems

As mentioned, the hip and knee joint centres were used to generate the embedded femoral coordinate system, and the knee and ankle joint centres were used to generate the embedded tibial coordinate system, according to the G&S convention (180). From the embedded femoral and tibial axes, the segmental angles were calculated using the widely accepted and used joint coordinate system (JCS), again proposed by G&S (180). The JCS uses two axes from the embedded axes (femoral and tibial) and the third axis, the floating axis, is calculated for each frame of the bowling trial by taking the cross product of the two embedded axes. The JCS enables easy relation of the calculated angles to clinical angles of extension/flexion, abduction/adduction, and internal/external rotation angles. These are the angles reported for both leading and trailing legs in Chapter 8.

6.11.2.4 Standardisation of Knee Angles

These knee angles for the men and women were standardised from 0 to 100% of the delivery stride, which is trailing foot strike to ball release. This standardisation allowed

for the comparison of knee angles among bowlers. For the men and women separately, the knee angles were averaged for each percent of the delivery stride. The results of this analysis are further described in Chapter 8.

6.11.3 Plug-In Gait Model Adaptation and Application for Bowlers

To compare the knee kinematics calculated using the G&S convention to the PIG model, Nexus 2.0 was used to reprocess the cleaned trials and apply the PIG model for the leading knee. To adapt the bowler marker set for PIG, the static trial for each bowler was first labelled using the bespoke bowler marker set. A static body model was then run to generate a thigh and tibia marker for each leg based on existing pelvis, knee, and ankle markers. A Static PIG model could then be applied. Next, the bowling trial was processed and a Dynamic PIG model was applied. The PIG model allowed for the external knee angles and moments to be exported directly from Nexus. The extension/flexion, abduction/adduction, and internal/external rotation angles and moments for the leading knee were included in the exported data.

The leading knee kinematics calculated by the PIG model were then compared with the averaged leading knee kinematics from the G&S convention for a random sample of bowlers. These comparisons are further described in Chapter 8.

6.11.4 Kinematic and Kinetic Parameter Extraction

The leading knee kinematic and kinetic parameters required for analyses were extracted from PIG model data. Leading knee angles and moments from the PIG model data were truncated to the delivery stride using the frame numbers procured from event identification described previously. The frame of leading leg strike was used to identify the external knee angles and moments at leading leg strike. The leading knee extension/flexion, abduction/adduction, and internal/external rotation angles and moments at leading leg strike were extracted. The knee angles were the local absolute

maximum angle within 40ms of leading leg foot strike, as described for a similar analysis of heel strike during walking (91). The external knee moments were normalised by each bowler's body weight in Stata.

6.12 Statistical Methods: Biomechanics Study

6.12.1 Linear Regression

Linear regression was used to test the association of biomechanics metrics with cartilage volume. The independent predictor variables were biomechanics metrics of leading leg knee angle at leading leg strike and leading leg knee moment at leading leg strike. The dependent outcome variables were normalised medial and lateral tibial cartilage measurements. The models were first unadjusted, then adjusted for age. Due to the small sample size, age was the only confounder included in adjusted models.

Four assumptions of linear regression were tested for each model (114,182):

1. The relationship between the independent and dependent variables is linear
2. The residuals are normally distributed
3. There is not multicollinearity in the data
4. Homoscedasticity

All of the linear regression analyses and assumption testing for this thesis were completed using Stata 14.2. The coefficient and p-value for each model was reported.

6.12.2 Spearman's Correlation Coefficient

Spearman's correlation coefficient was also calculated for each model. This non-parametric test was used in case a model did not meet the assumptions for linear regression.

6.13 Summary

This chapter described the methods for the assessment of the knee cartilage volume in the leading versus trailing legs of current elite fast bowlers, and the association of

kinematic and kinetic parameters during the bowling action with knee cartilage volume. The methods described in this chapter addressed participant recruitment, ethics approval, protocol development for the MRI study, image analysis, biomechanics data collection, cleaning, and event identification, and the required statistical methods. Further descriptions of analysis methods and the results of testing described in this chapter will be included in relevant methods and results sections of the experimental chapters.

Chapter 7 Compartmental Knee Cartilage in the Trailing Versus the Higher Loaded Leading Leg of Current Elite Fast Bowlers

7.1 Introduction

Chapter 5 noted the higher prevalences of self-reported injury, pain and GP-diagnosed osteoarthritis (OA) in the functionally dominant, or leading leg, than the functionally non-dominant, or trailing leg, of former elite bowlers. One explanation for this result may be the force differential seen between legs during the bowling action. The leading leg experiences approximately twice the force as the trailing leg during the bowling action (5). This increased force in the leading leg experienced over years of elite training and competition may have resulted in a deleterious response from the knee cartilage of the leading leg. Such a response may have subsequently contributed to the notably higher prevalence of pain and OA in the leading leg compared to the trailing leg of former elite bowlers.

The aim of this study is to test whether the load differential seen during the bowling action results in a significant difference in compartmental knee cartilage volume in the leading versus the trailing leg of current elite fast bowlers. The original hypothesis was that an increased load in the leading leg would be correlated with a greater cartilage volume. This aim was addressed for the current elite bowlers using the cross-sectional MRI study described in Chapter 6. The bowlers' trailing legs served as within-person controls, accounting for genetic factors while testing the effect of increased loading on the leading leg.

7.2 Methods

The methods for this analysis are described in detail in Sections 4.4 to 4.6. In brief, a cross-sectional observational study design was used for a convenient sample of ten male and six female current elite cricket fast bowlers. The bowlers were given self-report questionnaires and had MRI scans collected for both knees during routine data collection days at the end of the competitive season.

7.2.1 Lateral Tibia Compartment

The lateral tibia compartment for 5 leading legs and 6 trailing legs in the men were not completely captured in the MRI field of view. Only 2 male bowlers had both leading and trailing leg lateral tibial compartments completely captured in the MRI scans. Therefore, only 2 male bowlers were included in analyses of the lateral tibia compartment.

7.2.2 Image Analysis

The medial and lateral tibial cartilage volumes were normalised by the corresponding compartmental bone area; the compartmental tibial cartilage volume was divided by the respective compartmental tibial bone area. As described in section 4.5.2, the tibial bone area was actually a volume measurement of the bone cross-sectional area with a one-voxel thickness, but has been referred to as an "area" for simplicity. The raw and normalised medial and lateral tibial cartilage measurements, as well as the raw patellar cartilage volumes, are presented in the analysis.

7.2.3 Statistical Methods

7.2.3.1 Subject Characteristic Differences by Sex

Chi-squared tests and t-tests were used to determine whether the subject characteristics of male bowlers significantly differed from female bowlers. An interaction was assumed for the sex variable, but this was tested to determine whether the male and female bowler samples could be combined in order to increase the power of the results. A two-

sample t-test, assuming unequal variance, was used to compare continuous variables of age, years at an elite level, and average overs bowled per season as a professional. A chi-squared test was used to compare categorical variables of bowling arm, batting arm, and severe knee injury history.

7.2.3.2 Intra- and Inter-Observer Reliability

Reliability studies, described in detail in Chapter 6, tested the inter- and intra-observer reliability of the manual segmentation. The root-mean-square coefficient of variation (RMSCoV) and the intra-class correlation coefficient (ICC) were reported for intra- and inter-observer reliability of patellar and tibial cartilage volume and bone area measurements.

7.2.3.3 Leading Leg Versus Trailing Leg Cartilage Volume Comparison

The primary analysis was to determine whether to reject the null hypothesis that the true mean difference between leading and trailing leg compartmental cartilage volumes was zero. This was determined using a separate paired t-test for each compartment of cartilage volume: patella, medial tibia, lateral tibia, normalised medial tibia and normalised lateral tibia. Separate paired t-tests were also run for the total bowler sample, male bowlers, and female bowlers. To ensure a parametric test was appropriate for the cartilage volume measurements, the normality of the compartmental cartilage volumes was tested by plotting kernel density estimates with a normal distribution curve. All of the volumes were visually determined to be normally distributed. Therefore, the compartmental cartilage volumes were compared for the leading versus the trailing leg in each player using a parametric, paired t-test.

7.2.3.4 Secondary Analysis: Clinically Significant Difference

The secondary analysis was to investigate a clinically significant difference. This was determined by comparing the percent differences between the leading and trailing legs for compartmental cartilage volumes and normalised tibial measurements to the

established minimal clinically important difference (MCID) for knee cartilage volume change of 6.6% (183). The percent difference was calculated based on the hypothesis that the leading leg measurements would be greater, and so assumed the trailing leg to be the initial value.

7.3 Results

7.3.1 Subject Characteristics

Table 7.1 shows subject characteristics of the 16 male and female current elite bowlers included in this analysis.

7.3.1.1 Subject Characteristic Differences by Sex

There were no significant differences between male and female bowler subject characteristics ($p>0.05$). This allowed for male and female bowlers to be combined in analysis, as well as stratified by sex.

Table 7.1. Subject characteristics of male, female, and total sample of current elite bowlers.

	Male *(N=10)*	Female *(N=6)*	Total *(N=16)*
Age			
Mean (SD)	20.6 (3.0)	23.7 (4.0)	21.8 (3.6)
Range	17 - 26	20 - 31	17 - 31
Right-armed bowler (%)	90%	83%	88%
Right-armed batsmen (%)	80%	83%	81%
Years at an elite level, Mean (SD)	2.7 (2.6)	6.5 (3.6)	3.9 (3.5)
Average overs bowled per season as a professional, Mean (SD)	380 (156)	418 (168)	394 (156)
Severe Knee Injury History	60%	67%	63%
KOOS, Mean (SD)			
Pain	91 (15)	97 (4)	93 (13)
Symptoms	88 (13)	92 (9)	90 (11)
ADL	97 (6)	100 (0)	98 (5)
Sport/Recreation	89 (18)	94 (5)	91 (14)
QOL	89 (17)	94 (12)	91 (15)

The age of the bowlers ranged from 17 to 31 years, with a mean age of 21.8 years. The female bowlers were slightly older with a mean age of 23.7 compared to the males' 20.6 years, and had played at an elite level slightly longer with a mean of 6.5 years compared with the males' 2.7 years. 63% of the total bowler sample had a history of at least one severe knee injury. The men had slightly lower KOOS scores than the women. Compared with the average KOOS scores of similarly aged healthy participants in a previous study, the men had slightly lower KOOS scores and the women had comparable or above average KOOS scores (184).

7.3.2 Reliability Studies

The manual segmentation reliability studies demonstrated high reliability for cartilage volume and bone surface area measurements. The inter-observer reliability for the

medical student had an RMSCoV of 4.23% and an inter-observer ICC of 0.97; particularly given the student's lack of experience in MRI or segmentation, this demonstrated the soundness of the segmentation methods.

The intra-observer reliability for patellar cartilage volume had an RMSCoV of 2.85%, soundly within the range of 1.0 – 3.7% reported by previous studies; the intra-observer ICC for patellar cartilage volume was 0.91, indicating excellent reliability (162,164).

The intra-observer reliability for tibial bone surface area had an RMSCoV of 1.46% and ICC of 0.97 for the medial tibial surface, RMSCoV of 5.94% and ICC of 0.89 for the lateral tibial surface, and RMSCoV of 2.26% and ICC of 0.94 for the total tibial surface. These values are all within acceptable intra-observer ranges.

Samples of the knee MRI and segmentation volumes, as they appear in 3D Slicer software are shown in Figures 7.1 and 7.2.

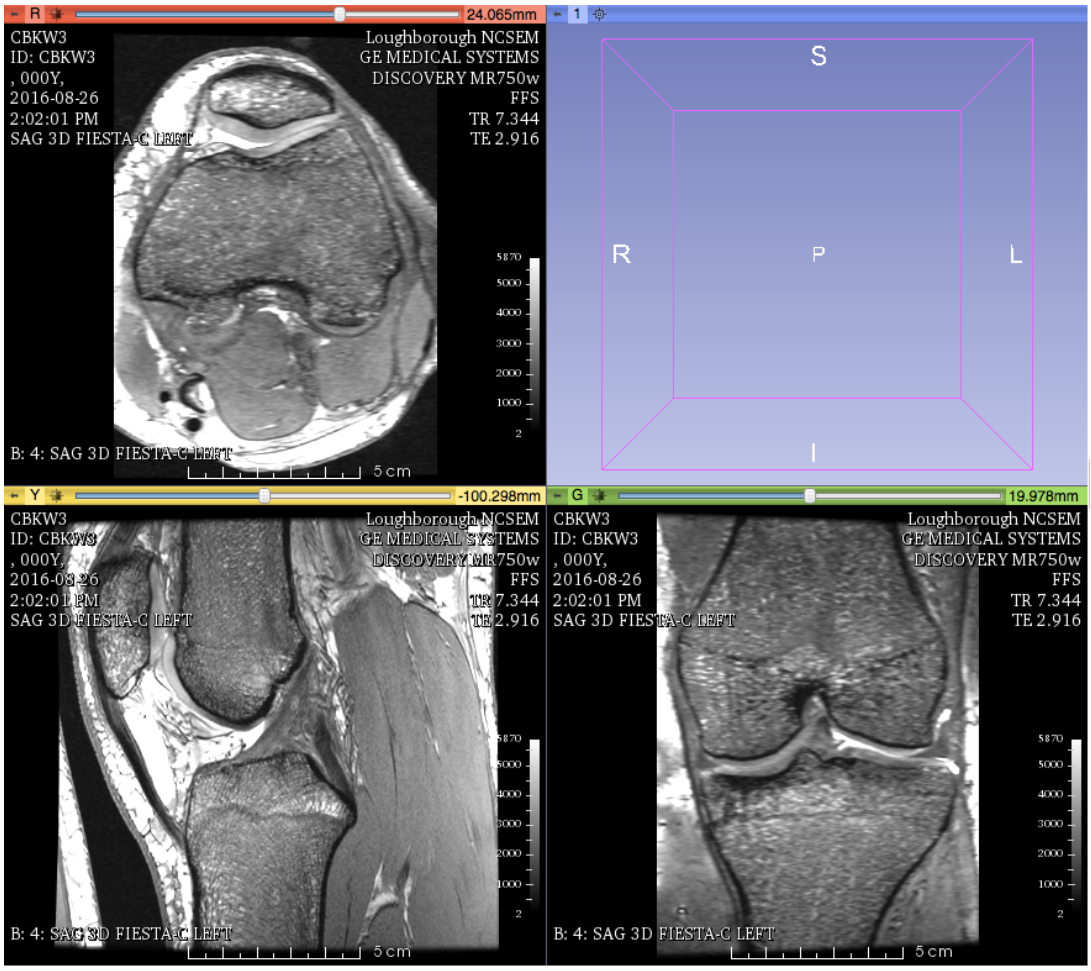


Figure 7.1. Three-plane view of a knee MRI as it appears in 3D Slicer.

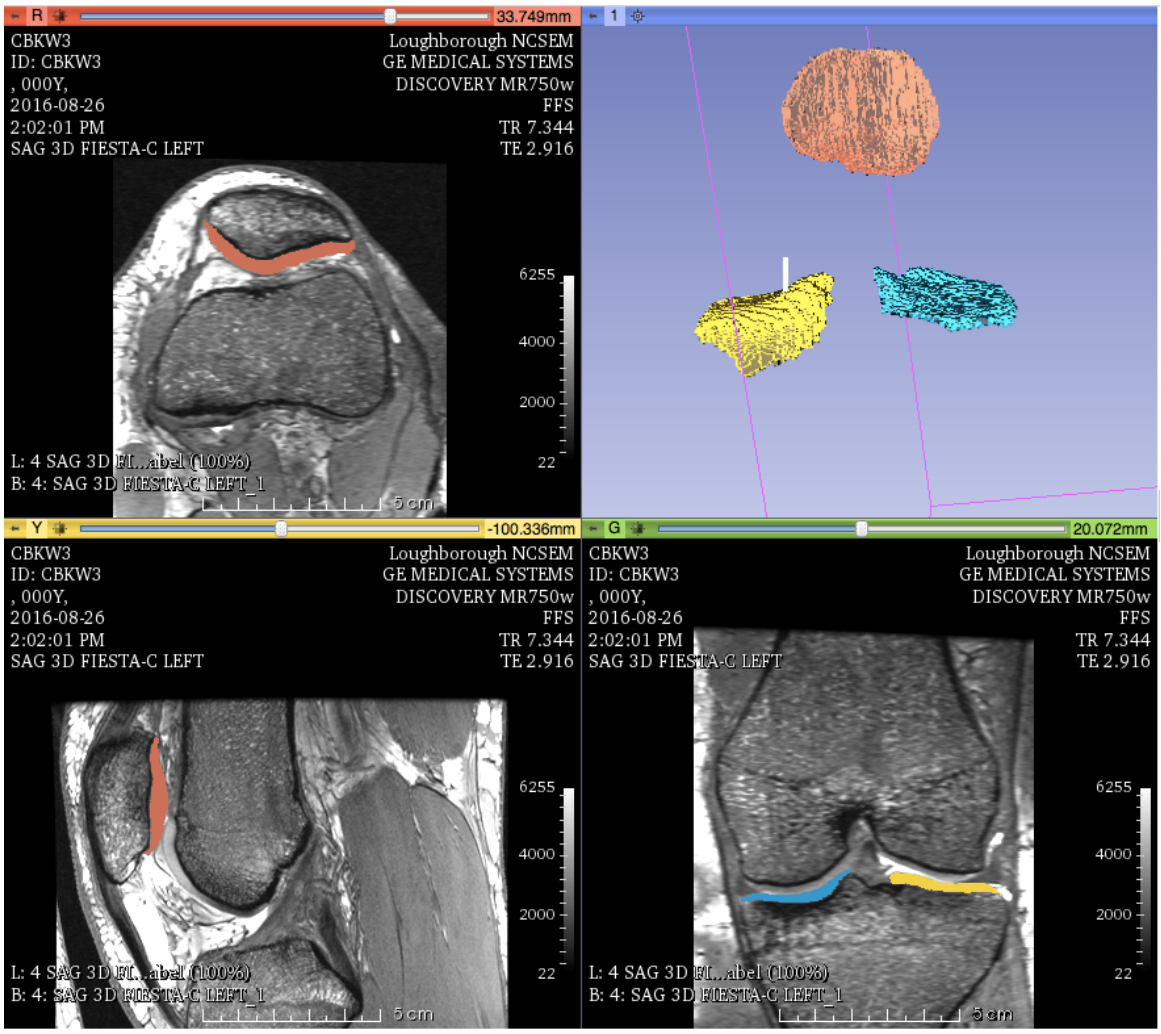


Figure 7.2. Three-plane view of a knee MRI as it appears in 3D Slicer, with patellar and tibial compartments segmented. The volume rendering of these compartments is shown in the top right frame.

7.3.3 Cartilage Volume Measurements

The average patellar and medial and lateral tibial cartilage volumes for the leading and trailing legs are shown in Figure 7.3, 7.4 and 7.5. Due to missing lateral compartment data in 8 male bowlers, the lateral compartment analyses include 2 male bowlers and 8 bowlers in the total sample. From these graphs, there is no significant difference between the leading leg and trailing leg in any analyses. The male bowlers appear to have larger compartmental cartilage volumes, though the medial tibia compartment does not appear significantly larger in the men.

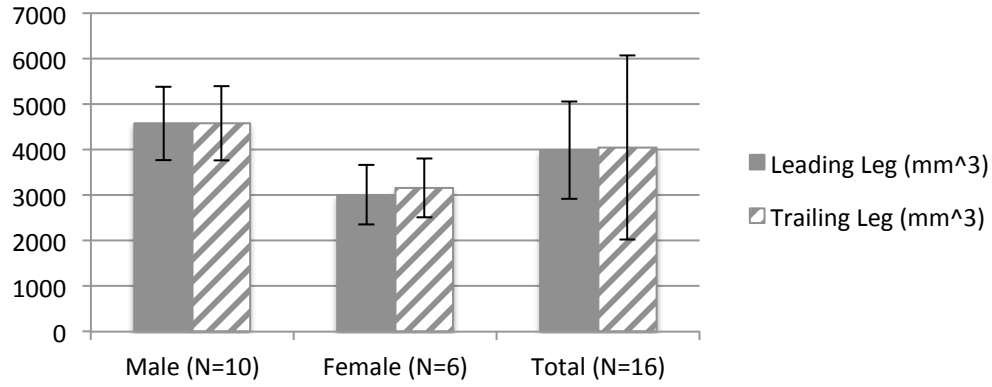


Figure 7.3. Mean and standard deviation of the leading and trailing leg patellar cartilage volumes for male, female, and combined bowler samples.

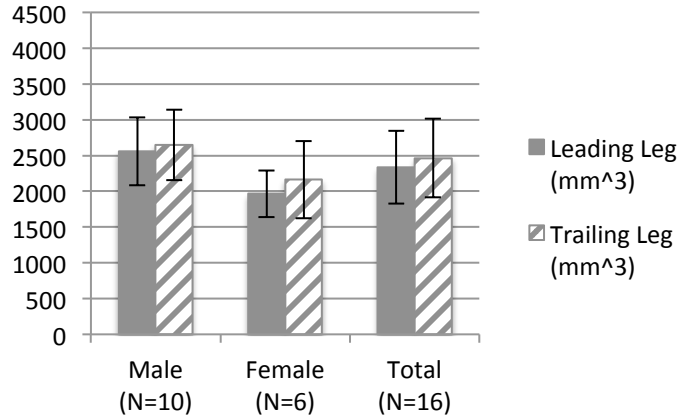


Figure 7.4. Mean and standard deviation of the medial tibial cartilage volumes for male, female, and combined bowler samples.

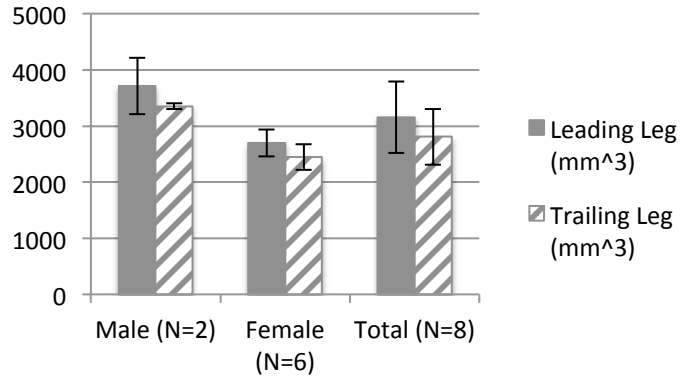


Figure 7.5. Mean and standard deviation of the lateral tibial cartilage volumes for male, female, and combined bowler samples.

7.3.4 Tibial Bone Area Measurements

The average medial tibial and lateral tibial bone areas are shown in Figures 7.6 and 7.7. The lateral compartment includes 2 male bowlers and the total sample analyses have a valid N=8 bowlers. Again, there does not appear to be a significant difference between the leading and trailing legs. The male bowlers appear to have larger bone areas than the female bowlers.

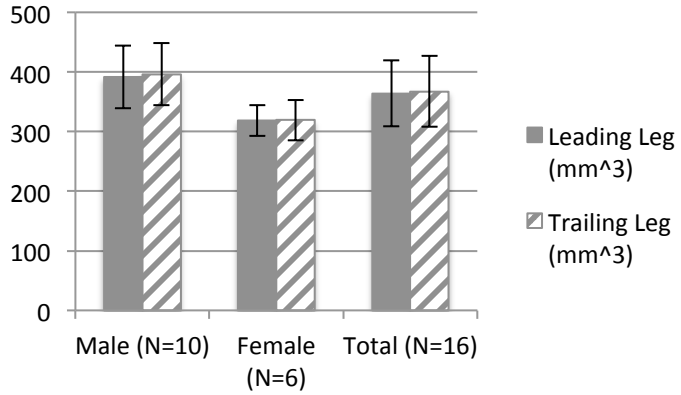


Figure 7.6. Mean and standard deviation of the medial tibial bone areas for male, female, and combined bowler samples.

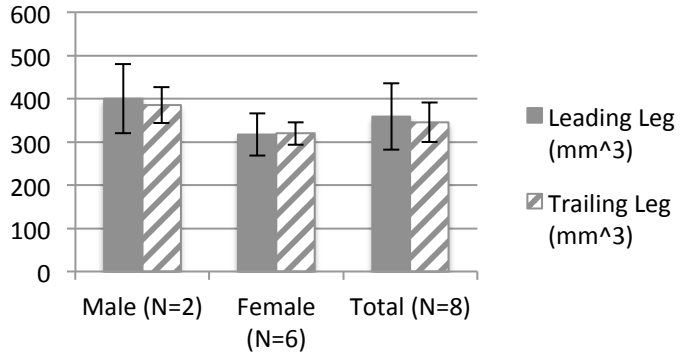


Figure 7.7. Mean and standard deviation of the lateral tibial bone areas for male, female, and combined bowler samples.

7.3.5 Normalised Tibial Cartilage Measurements

The average normalised medial and lateral tibial cartilage measurements are shown in Figures 7.8 and 7.9. The lateral compartment includes 2 male bowlers and the total

sample analyses have a valid N=8 bowlers. The normalised measurements appear to mitigate the sex differences that were seen in the raw cartilage volumes. The normalised medial tibia measurement does not appear to show any significant difference between leading and trailing legs. The normalised lateral tibia measurement appears to show a borderline significant difference between the leading and trailing legs of the female and total bowler samples.

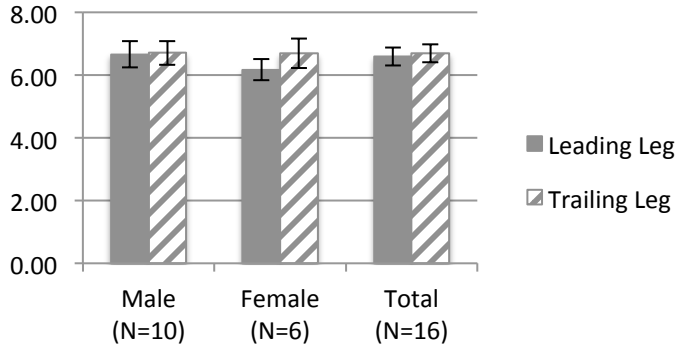


Figure 7.8. Mean and standard deviation of the normalised medial cartilage measurements (medial cartilage volume / medial tibial bone area) for male, female, and combined bowler samples.

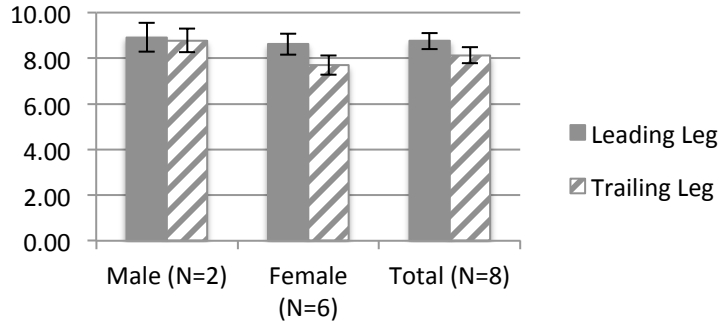


Figure 7.9. Mean and standard deviation of the normalised lateral cartilage measurements (lateral cartilage volume / lateral tibial bone area) for male, female, and combined bowler samples.

7.3.6 Leading Leg Versus Trailing Leg Cartilage Volume Comparison

The results from comparing the leading versus the trailing leg for each compartment for the male, female, and the combined bowler samples using paired t-tests are shown in

Table 7.2. The men's lateral tibia cartilage volume was not compared due to missing data.

Table 7.2. Paired t-test p-values for male, female, and combined bowler samples.

Compartment	Total (N=16) *P-value*	Men (N=10) *P-value*	Women (N=6) *P-value*
Patellar Cartilage Volume	0.52	0.96	0.34
Medial Tibia Cartilage Volume	0.11	0.35	0.21
Lateral Tibia Cartilage Volume	0.24*	--**	0.14
Medial Bone Surface Area	0.59	0.61	0.9
Lateral Bone Surface Area	0.42*	--**	0.86
Normalised Medial Tibia Cartilage Volume	0.49	0.92	0.23
Normalised Lateral Tibia Cartilage Volume	0.14*	--**	0.15
*N=8 due to missing lateral tibial compartments in the men			
**Not included due to missing lateral tibial compartments in the men			

There were no statistically significant differences between the cartilage volumes of the leading and trailing legs for the male, female, or combined bowler samples.

7.3.7 Secondary Analysis: Clinically Significant Difference

The percent differences for cartilage volumes and normalised tibial cartilage measurements are shown in Table 7.3, with differences greater than the MCID of 6.6% threshold in bold (183).

Table 7.3. Percent differences for compartmental cartilage volumes and normalised tibial measurements. Absolute differences greater than the 6.6% threshold proposed by Losina et al are shown in bold. Positive values suggest that the leading leg compartment was greater.

Compartment	Total (N=16)	Male (N=10)	Female (N=6)
Patellar Cartilage Volume	-1.5%	-0.1%	-4.7%
Medial Tibia Cartilage Volume	-5.2%	-3.4%	**-9.1%**
Lateral Tibia Cartilage Volume	**12.5%***	--**	**10.5%**
Normalised Medial Tibia Cartilage Volume	-1.6%	-0.7%	**-7.8%**
Normalised Lateral Tibia Cartilage Volume	**7.7%***	--**	**11.9%**
*N=8 due to missing lateral tibial compartments in the men			
**Not included due to missing lateral tibial compartments in the men			

The absolute percent differences for the raw and normalised lateral tibia cartilage measurements in the total sample were greater than the MCID. The raw and normalised lateral and medial tibia cartilage measurements for the female bowlers were greater than the MCID, though this result was not seen in the male bowlers. The female bowlers and the total sample showed greater cartilage measurements in the lateral tibia compartment of the leading leg. However, the female bowlers concurrently had lower cartilage measurements in the medial tibia compartment of the leading leg.

7.4 Discussion

This research is the first to investigate the effect of a regular load differential between legs on *in vivo* knee cartilage morphology. No statistically significant difference was found between the compartmental knee cartilage volumes of the leading versus the trailing legs for the male, female, or combined bowler samples. Secondary analysis found that the percent difference between legs was greater than the MCID in the raw and normalised lateral tibia cartilage volume measurements for the total sample, and for

the raw and normalised lateral and medial tibia cartilage volume measurements in the female bowlers.

7.4.1 Reliability

The manual segmentation protocol for this study, using 3D Slicer software, yielded excellent reliability. The inter-observer reliability for the patella, with an ICC of 0.97, is of particular note given the inexperience in MRI or image analysis of the first-year medical student that participated as the second observer. The inter-observer ICC demonstrated the success of the manual segmentation protocol developed for this study. Further, the intra-observer reliability studies showed the lead observer to have excellent reliability for this protocol. The intra-observer reliability was particularly important for this study because the lead observer segmented all of the reported volumes and measurements used in analysis. Other studies that used 3D Slicer software to manually segment knee cartilage reported comparable ICCs and root-mean-square coefficients of variation (RMSCoV) (102,163). Brem et al reported intra-observer RMSCoV of 1.1 – 1.8% and inter-observer RMSCoV of 2.3 – 3.3% at the tibia; this study had intra-observer RMSCoV of 2.8% and inter-observer RMSCoV of 4.2% (163). Hunter et al reported intra-observer ICC of 0.97 for the segmentation of the tibia and patella using 3D Slicer; this study had intra-observer ICC of 0.91 (102). The comparability of the RMSCoV and ICCs in this study relative to those in the cited studies demonstrates the high reliability for this manual segmentation protocol and the measurements reported.

7.4.2 Role of Genetic Factors

Using the trailing leg of the bowlers as the "control" compared to the higher loaded leading leg allowed this study to control for genetic factors when testing the effect of loading. Twin studies of monozygotic (MZ) and dizygotic (DZ) twin pairs have investigated the role of genetic factors on joint morphology. Two studies investigated

knee cartilage volume and hip joint space width, a proxy for hip cartilage thickness, in adult MZ and DZ twin pairs. Both studies found genetic factors to explain the majority of variance in cartilage morphology (101,102). Further, a study of healthy adults investigated side differences in cartilage thickness and volume, and found no significant difference within individuals and no significant effect of side dominance on cartilage thickness or volume (104). The statistically non-significant difference in cartilage volume between knees in this study is consistent with these results, supporting genetics as a major factor in cartilage morphology. The results of the secondary analysis, however, suggest that genetic factors do not entirely explain cartilage morphology. The greater volume seen in the leading leg's lateral compartment of the combined bowler sample suggests that loading and physical activity levels may still play a role in cartilage morphology and its maintenance in adulthood.

7.4.3 Increased Loading and Cartilage Metric

7.4.3.1 Leading Leg Versus Trailing Leg Cartilage Volume Comparison

The current study evaluated elite athletes using the metric of cartilage volume adjusted for bone size, but found no statistically significant difference due to increased loading in one leg. The results suggest that the metric of cartilage volume does not capture a statistically significant change in elite athletes' cartilage due to increased loading in one leg. Other studies using the metric of cartilage volume adjusted for bone size have shown a positive correlation of knee cartilage volume with more vigorous physical activity in community-based adults and adolescent children (88,185,186). However, studies using the metric of cartilage thickness did not find a statistically significant difference between elite athletes compared to inactive controls (82,84,85).

7.4.3.2 Secondary Analysis: Clinically Significant Difference

However, secondary analysis did show a clinically significant difference using the metric of cartilage volume adjusted for bone size. This may suggest that this study was

underpowered to detect a statistically significant result. The lateral tibia compartment had a greater cartilage volume in the leading leg; the female bowlers largely drove this result, as only two male bowlers were included in lateral tibia compartment analyses. The female bowlers also showed a clinically significant difference in the medial tibia compartment. The lack of a clinically significant difference in the men may be attributed to the length of their elite career. The female bowlers in this study had been playing at the elite level longer than the male bowlers: an average of 6.5 years for the women and 2.7 years for the men. Therefore, the women may have been playing long enough to see a significant difference due to the loading differential in bowling.

The direction of the difference in the female bowlers' medial tibia compartment, however, was the reverse of the lateral compartment. The medial tibia compartment showed a lower volume in the higher loaded leading leg compared to the trailing leg. Assuming the same forces were experienced in both medial and lateral compartments, this is not a biologically plausible result. Cartilage would be expected to respond to increased load in the same manner, regardless of the compartment. Therefore, it is hypothesized that the tibial compartments experience bowling loads differently. Perhaps the loads experienced by the lateral compartment are healthy loads, to which the cartilage adapts by increasing its volume. Conversely, the loads experienced by the medial compartment may be greater than the lateral compartment, resulting in injurious loading that decreases the cartilage volume. While gait literature has shown the medial knee compartment to experience an estimated 2.5 times greater load than the lateral knee compartment, the cricket bowling literature evaluated did not describe joint-specific loading patterns (64,187,188). Therefore, loading patterns in the knee during cricket fast bowling were further explored in the next chapter.

7.4.4 Handedness Side versus Functionally Dominant Side

The side of the clinically significant differences in this study were dependent upon the compartment of interest. The leading leg was on the "functionally dominant" side, as defined in Chapter 5, while the trailing leg tended to be on the "handedness" side of this study's bowlers. The clinically significantly higher lateral tibial cartilage measurements in the leading leg compared to the trailing leg supports the previous handedness research discussed in Chapter 5, which found handedness to be associated with the side of hip OA and joint replacement (149). As the trailing leg tended to be on the same side as the dominant hand, and tended to have lower lateral tibial cartilage, lateral compartment knee OA would be more likely to develop first on the trailing leg, or handedness, side.

Conversely, the clinically significantly lower medial tibial cartilage measurement in the leading leg compared to the trailing leg of female bowlers supports the higher prevalence of pain and OA on the functionally dominant side in the former elite bowlers in Chapter 5. A lower medial tibial cartilage measurement would make medial compartment knee OA more likely to develop first on the leading leg, or functionally dominant, side. However, the medial tibia compartment result was only found in the female bowlers; the difference in the male bowlers was not clinically significantly different. A larger sample size may improve the consistency of results for this study between knee compartments and provide further evidence for the association of the side of OA and either the handedness side or the functionally dominant side.

7.4.5 Inactive Controls

It is possible that while the load differential in the knees during the bowling action did not result in a statistically significant difference in cartilage volume, the years of elite physical activity of these bowlers may have increased the cartilage volume in both legs

compared to inactive controls. This study did not have an inactive control sample but the bowlers had a similar age and sex distribution to the Faber et al healthy, inactive control cohort, which included 9 women and 9 men, average age of 22.3 years (106). Considering the mean raw compartmental cartilage volumes reported for the inactive controls, the male and female bowlers in the present study appear to have greater cartilage volumes by as much as 1000 mm^3 in the patella and medial tibia in the men, and 700 mm^3 in the women. Cartilage thickness was not reported in Faber et al or this study, to compare with previous studies of elite athletes and inactive controls. Interpretation should be cautious in the comparison of these bowlers with the Faber et al cohort, as the previous study did not report a normalised cartilage volume, adjusted for bone size. Also, a different MRI and segmentation protocol was used, which further limits the comparability of results. Even so, the cartilage volume differences seen in the bowlers versus inactive participants may warrant investigation.

7.4.6 Strengths and Limitations

This study had a few noteworthy strengths and limitations. Analysing both knees within the bowlers was a substantial strength, as it allowed this study to account for person-level confounding factors that might affect cartilage morphology. For example, genetic factors could confidently be excluded as explanatory for any difference in cartilage volume. The statistically non-significant difference in compartmental cartilage volume suggests that genetic factors play a major role in cartilage morphology.

Another strength of this study was the reliability of the manual segmentation measurements. The manual segmentation had excellent reliability and allowed for the highest level of control over distinguishing between cartilage and surrounding tissue during segmentation. However, the method was exceptionally time-consuming. Automated and semi-automated segmentation methods have been developed for

cartilage, and while such methods were unavailable for the present study, future work would benefit from establishing collaborations to utilise existing methods. Automated or semi-automated methods would allow for even greater reliability and for larger sample sizes.

One limitation was this study's lack of an inactive control group. The study assumed that the force differential seen during the delivery stride of bowling would be sufficient increased loading to see any significant response in knee cartilage. Future work could recruit age-matched inactive controls, use the same MRI and segmentation protocol, and compare the effect of increased activity on cartilage volume, rather than the metric of cartilage thickness used in previous studies.

Another limitation was the small sample size, which may have been under-powered to detect statistically significant differences. This study's 16 elite bowlers were a convenient sample and of similar sample size to other studies of elite athletes, which recruited between 9 and 18 athletes, though these studies assessed cartilage thickness rather than cartilage volume (82–85). This study's sample was small compared to other studies of cartilage volume: Jones et al recruited 92 adolescent children for knee cartilage investigation, while Racunica et al investigated 297 healthy adults (185,186). An increased sample size, perhaps with a narrower range of age and years of elite play, would improve the power of the present study's results. Increased power would also help in determining whether the clinically significant difference in the female bowlers' medial and lateral tibia compartments was a true result.

7.5 Conclusions

This study investigated the effect of increased loading in one leg on knee compartmental cartilage volume. No statistically significant difference was found between the

compartmental cartilage volumes of the leading and trailing legs of the ten male, six female, or combined male and female elite bowler samples. Secondary analysis found clinically significant differences between the lateral tibia compartment measurements in the total sample and the lateral and medial tibia compartment measurements in the female bowlers. Further data is required on the loading pattern in the knee during bowling to assess the response of compartmental knee cartilage volume to loading.

Chapter 5 found higher prevalences of pain and OA in the leading leg of former bowlers. This chapter suggests that the previous result cannot be confidently attributed to the effects of increased loading in the leading leg on cartilage volume. However, this study's paired t-test results suggest that genetics play a major role in cartilage morphology.

Future studies should utilise larger sample sizes of elite bowlers of both sexes using semi-automated or automated segmentation, and investigate how these elite bowlers compare to inactive controls. Such work could provide further evidence for encouraging physical activity in adolescents and young adults to maximize cartilage volume accrual. Future work could also determine whether compartmental cartilage volume is correlated with the forces experienced during the bowling action. Such a study would provide further evidence for or against the mechanosensitivity of cartilage and could help to explain the clinically significant differences in the medial and lateral tibia compartments of the female bowlers.

7.6 Disclosure of Publications Including Portions of This Work

Portions of this work, specifically the patellar cartilage volume and tibial cartilage volume results, have been submitted and accepted as a first author poster presentation to the OARSI World Congress 2016, presented as an oral presentation to the British

Association for Sport and Exercise Medicine 2017, and as a first author poster presentation to the OARSI World Congress 2018 (189,190).

Chapter 8 Association of Leading Leg Knee Cartilage Volume with Bowling Kinematics and Kinetics in Current Elite Fast Bowlers

8.1 Introduction

The previous chapter found no statistically significant difference in compartmental cartilage volumes between the leading and trailing leg of current elite fast bowlers. Clinically significant differences were found in the lateral tibia compartment of the total bowler sample and in the medial and lateral tibia compartments of the female bowlers. The female bowlers showed their leading leg to have a larger lateral tibia measurement and a lesser medial tibia measurement than the trailing leg. Further understanding of the loading pattern of the leading leg during bowling would benefit interpretation of these results.

The previous chapter also noted that, compared to an inactive control sample from a previous study, these bowlers appeared to have greater cartilage volumes (106). Such a result is consistent with the findings from community-based children and adults that cartilage volume increased with physical activity levels (185,186). These previous studies of cartilage volume, however, did not assess the knee kinematics or kinetics during any activity, to determine if certain biomechanics parameters were correlated with the increased cartilage volume.

Previous gait studies have shown cartilage morphology correlates with certain knee moments and angles (90,91). For example, the flexion/extension angle of the knee at heel-strike of walking has been shown to correlate with the location of greatest knee cartilage thickness (90,91). The more extended the knee flexion angle was at heel-strike of walking, the further anterior was the location of the thickest medial femoral cartilage. Walking is a cyclic, load-bearing activity. Bowling causes the leading leg to experience

approximately six times body weight, which may demand adaptation similar to that seen from walking even though bowling loads are experienced less frequently than walking (5).

The aim of this study is to test the association of normalised knee cartilage measurements with bowling kinematic and kinetic parameters in current elite bowlers. This aim was addressed for the current elite bowlers using the cross-sectional biomechanics study described Chapter 6.

8.2 Methods

This study used an observational cross-sectional study design.

8.2.1 Participants

As described in Chapter 6, a sample of male and female bowlers, identified by the ECB as being of an elite standard, was recruited for this study. All data were collected during routine data collection days at the end of the players' competitive seasons. The men's data were collected in 2015 on the same day as the MRI scans described in the previous chapter; the women's data were collected in 2016 five weeks after MRI scanning.

8.2.2 Inclusion Criteria

Bowlers were included if they had been included in the MRI study and had complete knee biomechanics data. Complete knee biomechanics required that both knee markers were visible during the delivery stride of the analysed biomechanics trial. The resulting final sample size for this study was 10 male and 3 female bowlers.

8.2.2.1 Lateral Tibia Compartment

The lateral tibia compartment for 5 of the male bowlers' leading legs was not completely captured in the MRI field of view. Therefore, five male bowlers were included in analyses of the lateral tibia compartment.

8.2.3 Biomechanics Protocol

The data collection, data cleaning, event identification, and parameter calculation are described in detail in Chapter 6. For reference, kinetic and kinematic data for these bowlers were collected using a force plate and Vicon cameras (Vicon Motion Systems, Oxford, UK) during routine data collection in the indoor nets at the ECB National Cricket Performance Centre (Loughborough, UK). The result of data cleaning and event identification was one trial for each bowler with a clean leading foot strike on the force plate and the frame numbers of trailing foot strike, leading foot strike, and ball release for that trial.

8.2.4 Kinematic and Kinetic Parameter Extraction

The leading knee extension/flexion, abduction/adduction, and internal/external rotation angles and moments were extracted from Plug-In Gait (PIG) model data, as described in Chapter 6. The kinematic and kinetic parameters required for this study's analyses were then calculated: leading knee angle at leading leg strike for extension/flexion, abduction/adduction, and internal/external rotation, and leading knee moment at leading leg strike for extension/flexion, abduction/adduction, and internal/external rotation. The knee angles were the local maximum angle within 40ms of leading leg foot strike, as described for a similar analysis of heel strike during walking (91). The external knee moments were normalised by each bowler's body weight in Stata.

8.2.5 Knee Kinematics

The knee kinematics during the entire delivery stride were calculated using the Grood and Suntay (G&S) convention in MATLAB and using the PIG model. The leading knee kinematics could then be compared to ensure the PIG model had calculated a reasonable estimate of leading knee angles.

8.2.6 Statistical Methods

8.2.6.1 Subject Characteristic Differences by Sex

As in previous chapters, chi-squared tests and t-tests were used to determine whether the subject characteristics of male bowlers significantly differed from female bowlers. If the male and female participants did not have significantly different subject characteristics, all of the bowlers could be combined for each analysis; otherwise, the analyses must be stratified by sex.

8.2.6.2 Missing versus Non-Missing

A missing versus non-missing analysis, using chi-squared tests and t-tests, compared the characteristics of participants included in complete case analysis versus those excluded from analysis due to missing biomechanics data. Missing versus non-missing analysis evaluated how representative the sample of former cricketers included in analysis was compared to those excluded for missing data.

8.2.6.3 Linear Regression

Linear regression models were used in Stata 14.2 to evaluate the association of the kinetic and kinematic parameters with the normalised medial and lateral tibial cartilage measurements of the leading knee. Kinetic and kinematic parameters were the independent variables, while medial and lateral cartilage measurements were the dependent variables in the regression models. A separate model was used for each angle and moment, and separate models were used for medial and lateral cartilage measurements. Complete case analysis was used where lateral tibial cartilage

measurements were not available due to missing data. Linear regression models were first unadjusted, then adjusted for age. The linear regression assumptions were tested for each model.

8.2.6.4 Spearman's Correlation Coefficient

A Spearman's correlation coefficient was also calculated for each model. This non-parametric test was used in case the assumptions for linear regression were not met.

8.3 Results

8.3.1 Subject Characteristics

Table 8.1 shows the subject characteristics of the 10 male and 3 female current elite bowlers included in this analysis.

8.3.1.1 Subject Characteristics Differences by Sex

Chi-squared tests and t-tests showed that, though the female bowlers had a slightly older mean age and longer mean number of years at an elite level, the male bowlers were not significantly different from the female bowlers included in this analysis for any subject characteristics ($p>0.05$). This allowed for male and female bowlers to be combined in linear regression models.

8.3.1.2 Missing versus Non-Missing

A missing versus non-missing analysis compared the subject characteristics of the cricketers with and without missing biomechanics data. Two-sample t-tests for continuous variables and chi-squared tests for categorical variables did not show the characteristics to be significantly different for missing versus non-missing cricketers ($p<0.05$). This meant that the bowlers included in this analysis were representative of those included in the previous, MRI study.

Table 8.1. Subject characteristics of male and female current elite bowlers included in regression analysis.

	Male *(N=10)*	Female *(N=3)*
Age		
Mean (SD)	20.6 (3.0)	26 (4.3)
Range	17 - 26	23 - 31
Right-armed bowler (%)	90%	100%
Right-armed batsmen (%)	80%	100%
Years at an elite level, Mean (SD)	2.7 (2.6)	7.3 (4.0)
Average overs bowled per season as a professional, Mean (SD)	380 (156)	370 (231)
Severe Knee Injury History	60%	67%
KOOS, Mean (SD)		
Pain	91 (15)	99 (2)
Symptoms	88 (13)	90 (13)
ADL	97 (6)	100 (0)
Sport/Recreation	89 (18)	97 (6)
QOL	89 (17)	100 (0)

8.3.2 Knee Kinematics

The knee kinematics calculated using the G&S convention were standardised from zero to one hundred percent of the delivery stride. The average and standard deviation of the leading and trailing leg angles were plotted separately for the men and women. The plots of the average leading and trailing knee angles and the standard deviation envelope for the men and women are shown in Figures 8.1 and 8.2. Neither kinematic nor kinetic data were filtered for this study's analyses.

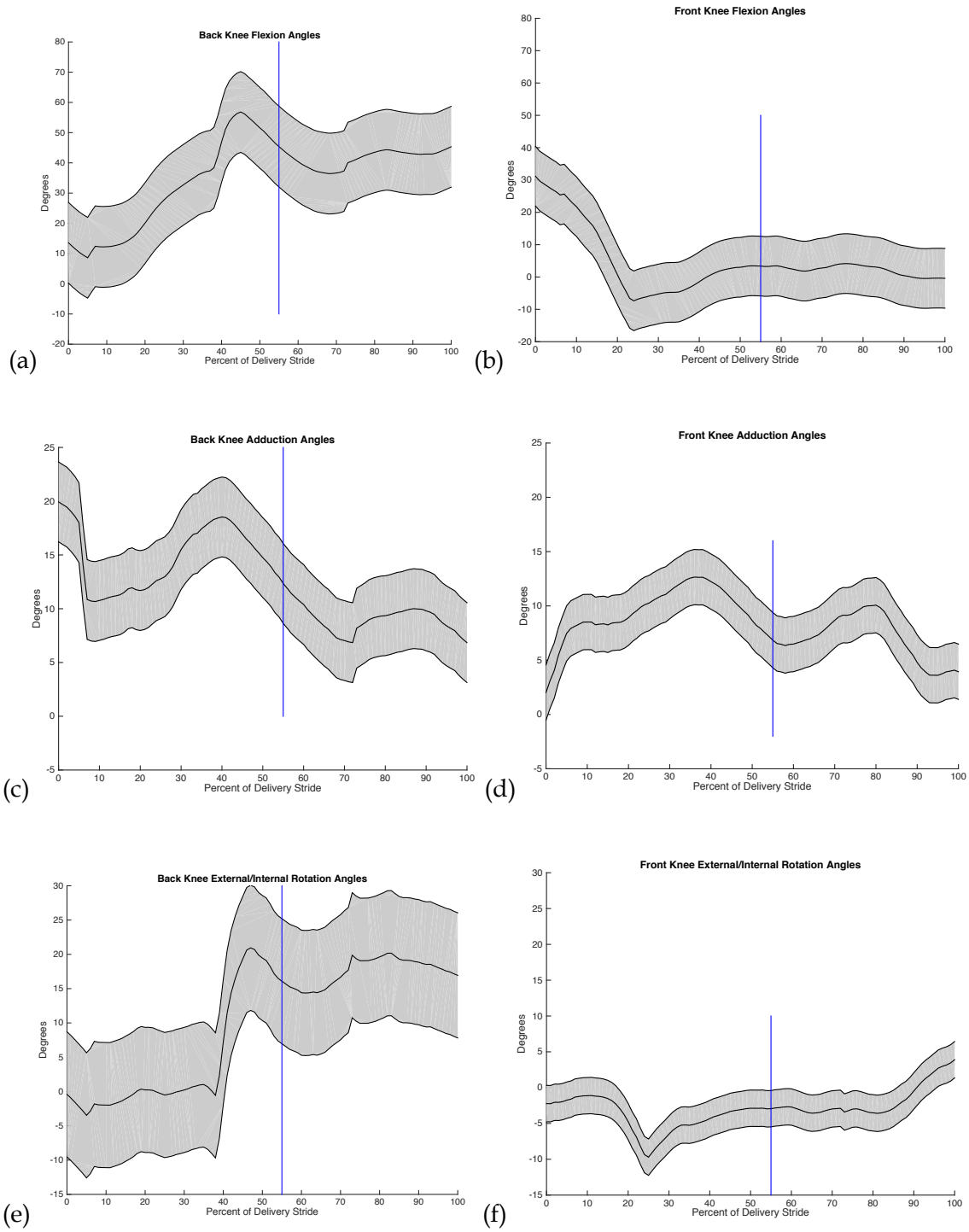


Figure 8.1. Women's knee angles through the delivery stride: trailing knee (a) flexion/extension, (c) adduction/abduction, (e) internal/external rotation; leading knee (b) flexion/extension, (d) adduction/abduction, (f) internal/external rotation. The average time of leading foot strike is indicated with a vertical line. Flexion, adduction, and external rotation were defined as positive.

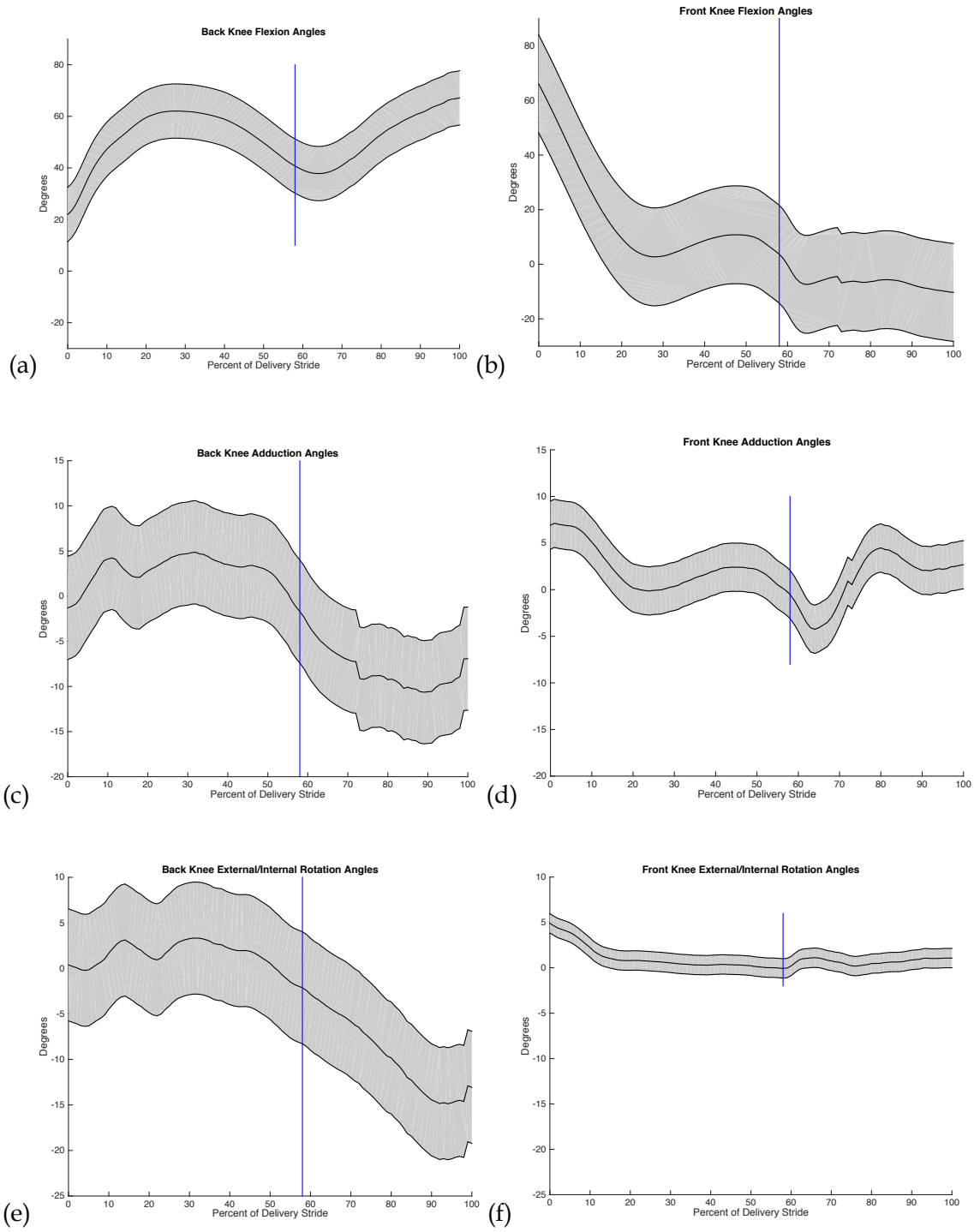


Figure 8.2. Men's knee angles through the delivery stride: leading knee (a) flexion/extension, (c) adduction/abduction, (e) internal/external rotation; trailing knee (b) flexion/extension, (d) adduction/abduction, (f) internal/external rotation. The average time of leading foot strike is indicated with a vertical line. Flexion, adduction, and external rotation were defined as positive.

8.3.2.1 Knee Kinematics Interpretation

The plots of the bowlers' knee kinematics are easily interpreted to show the delivery stride of the male and female bowlers.

8.3.2.1.1 Flexion/Extension: Trailing Knee

The trailing leg begins the delivery stride at trailing foot strike with around 15 – 20 degrees of knee flexion. Trailing knee flexion increases as the leg takes the weight of the body, then peaks and goes into extension as the player jumps off the trailing leg and into leading foot strike. From leading foot strike, the trailing knee returns to greater flexion as the player prepares for the follow through stride. This trailing knee flexion after leading foot strike appears more pronounced in the men than the women.

8.3.2.1.2 Flexion/Extension: Leading Knee

The leading leg begins at about 30 degrees of knee flexion in the women, and 60 degrees of knee flexion in the men during trailing foot strike. The knee then extends, or even hyperextends in some players, as the player moves the leading leg forwards, preparing for leading foot strike. From leading foot strike, both the men and women maintain their knee flexion angle while they use their leading leg as a lever until ball release.

8.3.2.1.3 Internal/External Rotation: Trailing Knee

The trailing knee starts at about zero degrees rotation during trailing foot strike for men and women. The men and women appear to have differing approaches in trailing knee rotation between leading foot strike and ball release. The men externally rotate their trailing leg knee after leading foot strike, while the women internally rotate their trailing leg knee.

8.3.2.1.4 Internal/External Rotation: Leading Knee

Both the men and women have some level of external rotation in the leading knee as the leading leg extends after trailing foot strike, but returns to zero degrees rotation before

leading foot strike. The men maintain this zero degree knee rotation in the leading leg for the delivery stride, while the women tend to have some internal rotation just before ball release.

8.3.2.1.5 Abduction/Adduction: Trailing Knee

The men and women appear to have differing trends in adduction and abduction for the trailing leg. For the men's trailing leg, the knee adducts slightly as the trailing leg takes the weight of the body and moves to leading foot strike, then abducts as the player moves into ball release. The women's trailing knee starts at a relatively large adduction angle, sharply abducting as the trailing leg takes the weight of the body and then moves into a peak knee adduction as the player jumps from the trailing leg into leading foot strike, when the knee abducts towards a more constant adduction angle of about 5 degrees.

8.3.2.1.6 Abduction/Adduction: Leading Knee

The men and women also appear to have differing trends in adduction and abduction for the leading leg. The men's leading leg abducts to close to zero degrees in preparation for leading foot strike, reaches a peak of abduction after leading foot strike, and adducts slightly before ball release. The women's leading knee goes into further adduction as the leading leg extends for leading foot strike, reaching a peak adduction just after the leading leg is full extended, and then abducts towards about 5 degrees of adduction for leading foot strike, finally moving towards zero degrees of adduction between leading foot strike and ball release.

8.3.2.1.7 Comparison with Plug-In Gait Model Knee Kinematics

The men's leading knee flexion/extension angles were compared between the PIG model estimation and the G&S convention. The PIG knee flexion angles and G&S knee flexion angles are shown in Figures 8.3 and 8.4. Flexion was defined as positive.

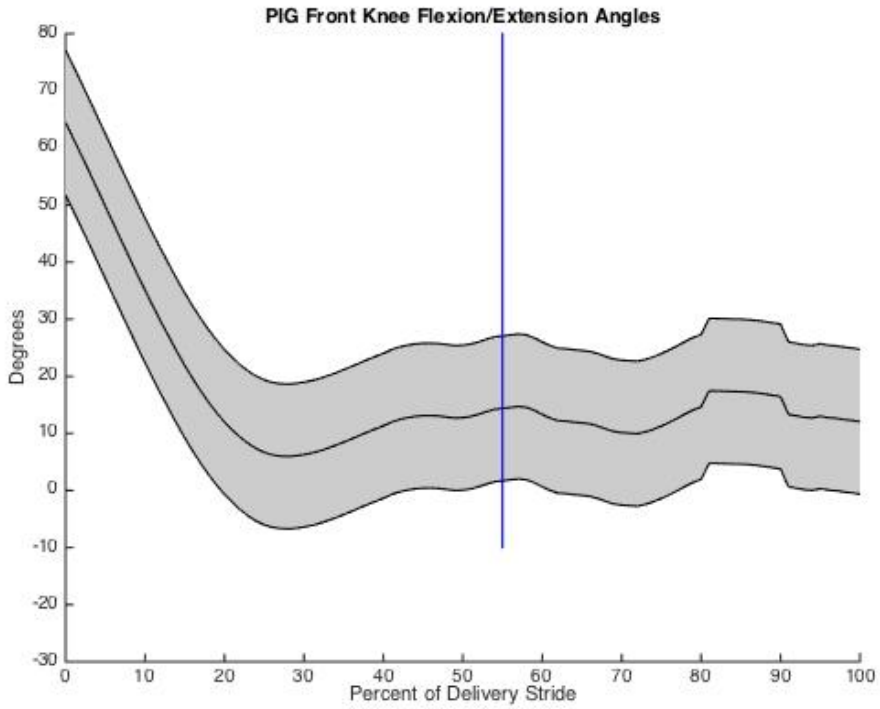


Figure 8.3. PIG model estimation of the male bowlers' leading knee flexion angles through the delivery stride.

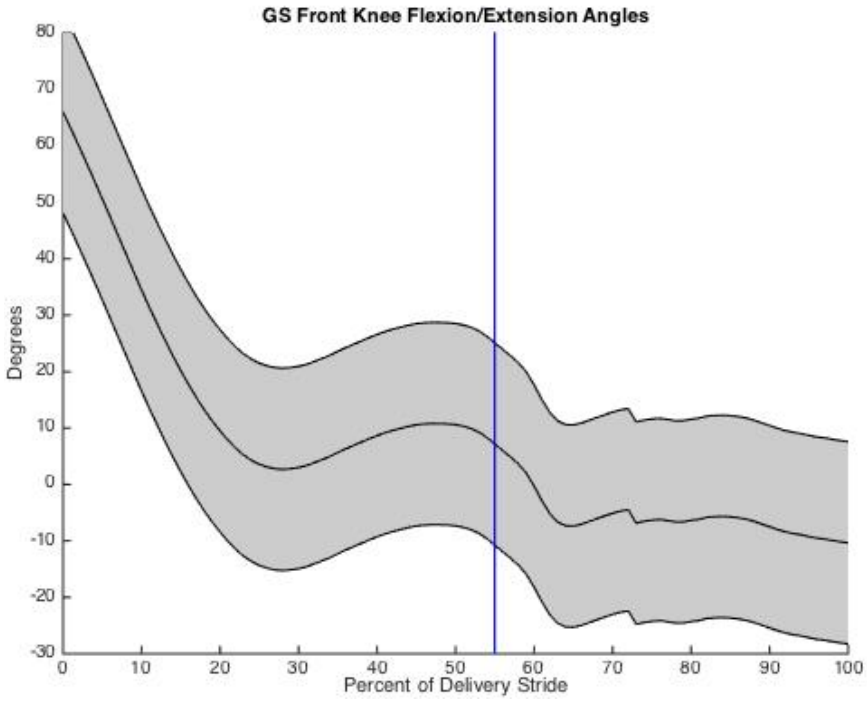


Figure 8.4. G&S estimation of the male bowlers' leading knee flexion angles through the delivery stride.

Compared with the PIG flexion angles, the G&S angles deviated into hyperextension after leading leg strike. This deviation highlights the limitations of estimating key

markers for the PIG model (the thigh and tibia). However, up to and including the leading leg strike, the PIG knee angles were determined to be comparable to the G&S calculations. Therefore, the kinetic and kinematic parameters at leading leg strike generated by the PIG model were used in linear regression analysis.

8.3.3 Kinematic and Kinetic Parameters

The kinematic and kinetic parameters of leading knee angle at leading leg strike for extension/flexion, abduction/adduction, and internal/external rotation, and leading knee moment at leading leg strike for extension/flexion, abduction/adduction, and internal/external rotation were extracted. These parameters are shown in Tables 8.2 and 8.3.

Table 8.2. Mean and range of the leading leg knee angles (in degrees) at leading leg strike.

Knee Angle	Mean	Range
Flexion	14.27	2.93 - 25.02
Extension	2.71	-8.67 - 12.47
Abduction	2.71	-2.40 - 7.96
Adduction	-1.48	-11.16 - 7.96
Internal rotation	8.61	-9.22 - 20.73
External rotation	0.87	-15.25 - 17.58

Table 8.3. Mean and range of the leading leg knee moments (in Newton-meters) at leading leg strike.

Knee Moment	Mean	Range
Flexion/Extension	565.50	-2858.14 - 6122.23
Ab/Adduction	-194.16	-2324.37 - 4811.99
Int/External Rotation	51.83	-978.60 - 1083.60

8.3.4 Normalised Tibial Cartilage Measurements

As described in the previous chapter, the medial and lateral tibial cartilage volumes were normalised by bone surface area. For reference with the linear regression coefficients, the normalised medial and lateral tibial cartilage measurements for the

leading leg are shown in Figures 8.5 and 8.6. It should be noted that the values in these figures differ from those in Chapter 7 because 3 female bowlers included in the previous analysis were excluded from the present analysis due to missing biomechanics data and the leading leg lateral tibial cartilage volume was available for 5 male bowlers.

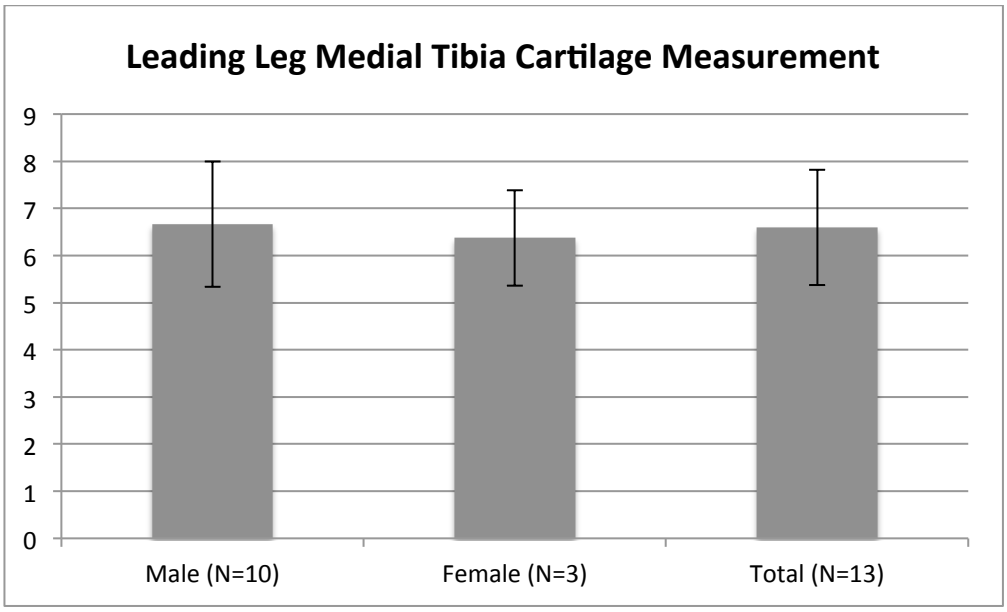


Figure 8.5. Mean and standard deviation of the leading leg normalised medial tibia cartilage measurements (medial tibial cartilage volume / medial tibial bone surface area) for male, female, and combined bowler samples.

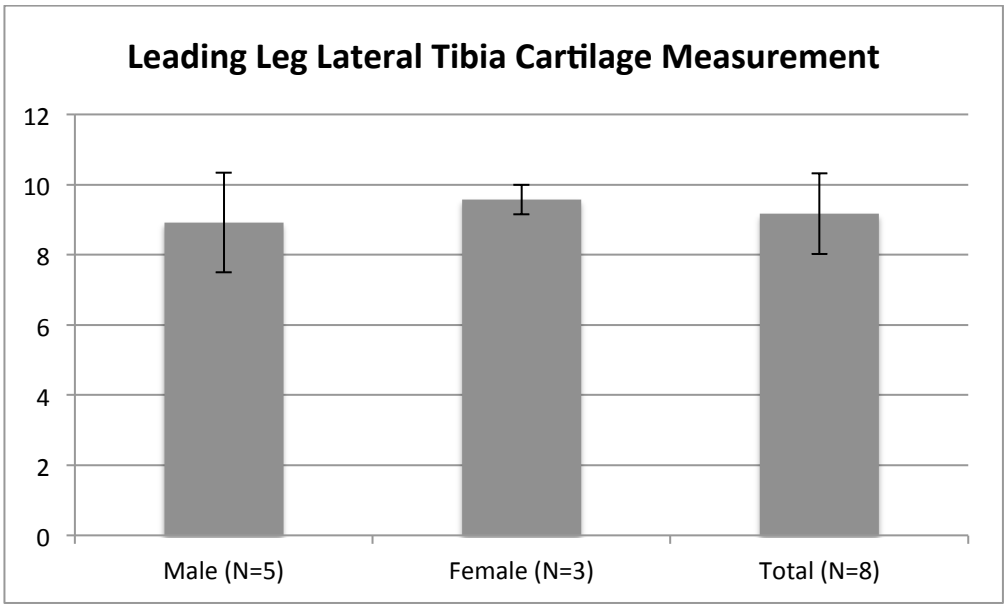


Figure 8.6. Mean and standard deviation of the normalised lateral tibia cartilage measurements (lateral tibial cartilage volume / lateral tibial bone surface area) for male, female, and combined bowler samples.

8.3.5 Linear Regression and Spearman's Coefficient Results

Linear regression was used to evaluate the association of the external knee angles and moments at leading leg strike with the normalised medial and lateral tibial cartilage measurements.

8.3.5.1 Knee Angle Results

The results from knee angle regression models and the Spearman's correlation coefficient for each model are shown in Tables 8.4.

Table 8.4. Coefficients and p-values from linear regression models: dependent variable of the leading leg knee angle at leading leg strike (within 40ms of foot strike) and independent variable of the normalised medial and lateral tibial cartilage measurements of the leading leg.

Cartilage Compartment	Knee Angle	Unadjusted		Age-Adjusted		Spearman's Coefficient
		p-value	Coefficient	*p-value*	Coefficient	
Normalised Medial Tibial Cartilage Measurement (N=13)	Flexion	0.706	-0.019	0.831	-0.012	0.831
	Extension	0.206	-0.073	0.272	-0.065	0.263
	Abduction	0.321	0.117	0.283	0.105	0.364
	Adduction	0.375	0.074	0.281	0.086	0.845
	Internal Rotation	0.613	-0.021	0.845	-0.009	0.603
	External Rotation	0.467	-0.024	0.726	-0.014	0.578
Normalised Lateral Tibial Cartilage Measurement (N=8)	Flexion	0.846	0.015	0.897	0.010	0.823
	Extension	0.972	0.003	0.997	0.000	0.911
	Abduction	0.709	-0.073	0.863	-0.042	0.911
	Adduction	0.287	0.105	0.256	0.113	0.651
	Internal Rotation	0.487	-0.031	0.450	-0.040	0.385
	External Rotation	0.345	-0.041	0.341	-0.049	0.420

The regression models for the knee angles did not show a significant association between any knee angles and either the normalised medial or lateral tibial measurements.

8.3.5.2 Knee Moment Results

The results from knee moment regression models and the Spearman's correlation coefficient for each model are shown in Tables 8.5.

Table 8.5. Coefficients and p-values from linear regression models: dependent variable of the leading leg knee moment at leading leg strike and independent variable of the normalised medial and lateral tibial cartilage measurements of the leading leg. Significant results (p<0.05) are shown in bold.

Cartilage Compartment	Knee Moment	Unadjusted		Age-Adjusted		Spearman's Coefficient
		p-value	Coefficient	*p-value*	Coefficient	
Normalised Medial Tibial Cartilage Measurement (N=13)	Flex/Extension	0.644	0.007	0.360	0.014	0.734
	Ab/Adduction	0.198	-0.013	0.286	-0.011	0.642
	Int/External Rotation	0.057	-0.088	0.083	-0.082	0.029
Normalised Lateral Tibial Cartilage Measurement (N=8)	**Flex/Extension**	**0.020**	**0.043**	**0.035**	**0.043**	0.102
	Ab/Adduction	**0.042**	**0.024**	0.061	0.023	0.120
	Int/External Rotation	0.054	0.113	0.071	0.119	0.531

The regression models for the knee moments at leading leg strike showed a significant association between the leading knee flexion/extension moment and the normalised lateral tibia measurement, which was maintained when the model was adjusted for age.

The flexion moment is defined as positive within PIG, meaning that a positively increased flexion/extension moment acts as shown in Figure 8.7. This sign convention would suggest that a positively increased flexion/extension moment should act downward in the posterior region of the contact area of the tibia and upward in the anterior region of the contact area of the tibia.

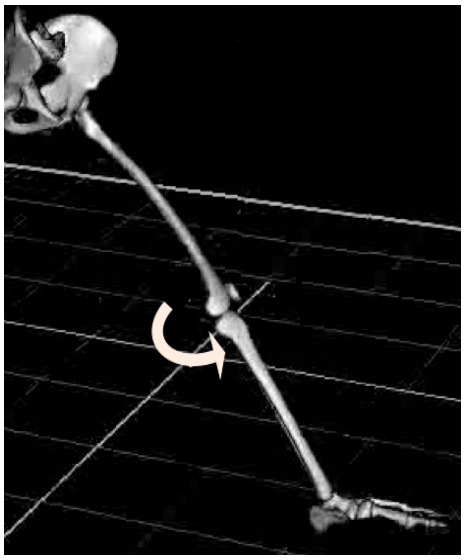


Figure 8.7. Diagram of the direction of action of a positive knee flexion moment.

A significant association was also found between the leading knee abduction/adduction moment and the normalised lateral tibia measurement, though the significance was attenuated to $p>0.05$ when adjusted for age. The abduction moment is defined as positive within PIG, meaning that a positively increased abduction/adduction moment acts as shown in Figure 8.8. This sign convention would suggest that a positively increased abduction/adduction moment would increase the contact force on the medial compartment of the tibia, and decrease that on the lateral compartment of the tibia.

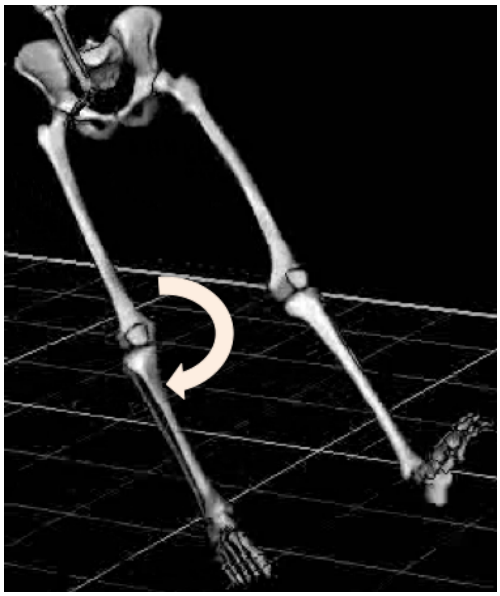


Figure 8.8. Diagram of the direction of action of a positive knee abduction moment.

8.4 Discussion

This study investigated the relationship between kinematic and kinetic parameters of the delivery stride of fast bowling and cartilage volume measurements. Previous studies of the relationship between kinematic and kinetic parameters and cartilage volume or thickness measurements have focused on walking; this study was the first to investigate these relationships for fast bowling. The kinematic parameters were the external knee angles within 40ms of leading leg strike. The kinetic parameters were the moments at leading leg strike of the delivery stride. Only the flexion/extension and abduction/adduction moment at leading leg strike had a significant association with the leading leg normalised lateral tibia cartilage measurement. No parameters were significantly associated with the leading leg normalised medial tibia cartilage measurement.

8.4.1 Lateral Tibia Compartment

Significant associations were only found between knee moments and the lateral tibia compartment. This was consistent with the clinically significant differences in the total sample from the previous chapter, which were only found in the lateral tibia compartment. The previous chapter found the lateral tibia compartment to have a greater cartilage volume in the leading knee than the trailing knee. This study's results

showed that the leading leg lateral tibia cartilage measurements were positively associated with increased knee flexion/extension and abduction/adduction moments.

The result in the lateral tibia compartment is consistent with a previous study of former anterior cruciate ligament reconstruction (ACLR) patients. The previous study found a positive correlation between maximum tibial contact force and cartilage volume in only the lateral, and not the medial, compartment of patients 2 to 3 years after ACLR and with meniscal injury (191). The healthy adults in the previous study showed a positive correlation between maximum tibial contact force during walking and cartilage volume in both the medial and lateral tibia (191). Though this study addressed knee moments rather than contact forces, and the bowlers in this study did not have a history of ACLR, they demonstrated a similar relationship between moments at leading foot strike and cartilage volume in the lateral but not medial tibial compartment as the ACLR participants with meniscal injury.

8.4.1.1 Size and Kinetic Relationships: Medial versus Lateral Tibia

The method used to calculate knee moments in this study did not provide the resolution to confidently determine whether the moments in the lateral compartment were greater than, less than, or equal to those of the medial compartment. Evaluation of the normalised cartilage measurements of the medial and lateral tibia shows the lateral compartment measurements to be greater than the medial compartment for the entire bowler sample. A similar finding was reported in Saxby et al for healthy and ACLR participants (191).

The differing size and kinetic relationships seen in the medial versus lateral tibia compartments may be adaptations to the forces experienced in each compartment. The relationship seen between the abduction/adduction moment and the lateral tibia compartment supports this hypothesis. A higher abduction moment will be expected to shift the downward contact force to the medial tibia compartment. While still providing mechanical stimulation to the lateral compartment, an increased abduction moment may allow the lateral compartment to avoid deleterious loading. However, if this were the case, the medial tibia compartment would be expected to demonstrate an equally significant and opposite relationship with abduction/adduction moments, which was not found in this sample of bowlers.

One alternative hypothesis is that a genetic reason exists for the morphological and kinetic relationship differences between lateral and medial compartments seen in this study and Saxby et al (191).

8.4.2 Kinematic Parameters

The knee angles of the leading and trailing knees, as calculated by the G&S convention, could be interpreted to represent the delivery stride for the male and female bowlers. The kinematic graphs of the delivery stride demonstrated the similar trend in knee angles for the men and for the women, with reasonable standard deviation envelopes. These graphs are novel, as no known studies of male or female bowlers have provided all of the knee kinematics for the leading and trailing legs through the delivery stride.

While previous studies showed walking kinematics, particularly knee angles at heel-strike, to be associated with cartilage thickness, this study found no significant association between cartilage volume and kinematic parameters (90,91). The leading leg foot strike during fast bowling was expected to be an exaggerated version of the heel-strike during walking and to demonstrate a similar association with cartilage morphology to that seen at peak extension during heel-strike (91). However, the kinematics during bowling may vary between deliveries more than the cyclic motion of walking, contributing to the non-significant result. Further, while these elite bowlers performed the bowling action regularly through their training and competition, they did not do so as frequently as walking. Therefore, the kinematics during the delivery stride may not be experienced frequently enough to have the same associations with cartilage morphology as those of gait kinematics.

8.4.3 Kinetic Parameters

The flexion/extension and abduction/adduction moments at leading leg strike were significantly associated with the normalised lateral tibia measurement. This study addressed the moment about an axis at leading leg strike, whether that moment was positive or negative. Not all bowlers were in positive extension or abduction at leading leg strike, with some in negative flexion or adduction. The positive correlation with these moments and lateral tibia cartilage suggests, then, that the normalised lateral tibia cartilage measurements increase as the bowlers' moments become more positive towards greater extension or abduction. As moments at leading leg strike became more negative in greater flexion or adduction, lateral tibia cartilage measurements decreased.

This relationship supports the findings from community-based children and adults, which suggest that cartilage volume can be increased with physical activity levels and further points to specific knee kinetics that are associated with increased cartilage volume measurements (88,186).

The relationship seen for knee adduction moment at leading leg strike and the lateral tibia compartment was different to that of a previous study of cartilage volume, bone size, and walking kinetics in healthy women (192). Jackson et al found only a relationship between peak knee adduction moment in late stance phase of walking with medial tibial bone surface area (192). No relationship was found between knee adduction moment and tibial cartilage volume, though the previous study did not standardise the cartilage volumes by bone size as in this study.

A previous gait study of OA patients showed that increased peak knee flexion moment was associated with cartilage thinning over 5 years (96). Gait studies have also shown peak knee adduction moment during walking to be associated with cartilage thickness in OA patients and healthy adults, with one study demonstrating a negative correlation between increased loading and cartilage thickness in OA patients (64,96,193). Future work should follow up these bowlers with MRI scans to determine if similar trends are seen in cartilage volume for bowling kinetics as in cartilage thickness for gait.

While the mentioned studies had identified knee flexion/extension and abduction/adduction moments during walking as related to cartilage morphology, no studies had investigated this relationship for bowling. The previous chapter found a clinically significantly greater cartilage volume in the lateral tibia compartment of the leading leg than the trailing leg; this study's results suggest that the lateral tibial cartilage morphology may be sensitive to certain loading patterns during bowling.

8.4.4 Limitations

This study had a few limitations of note. The kinetic and kinematic data collection used in this study has limitations in the accuracy of its estimation of the motion of the skeleton. The marker placement, meant to estimate bony landmarks, was not validated with the actual bony landmark during MRI. Future studies should mark on the participant's skin where a marker has been placed during biomechanics data collection; cod liver oil capsules can then be used in place of the markers during the MRI. Cod liver oil capsules are visible on MRI and would better inform how accurate the marker

placement has been during biomechanics data collection. This method has limitations of its own, as soft tissue motion will still slightly vary the placement of a marker during activity. Lying down in the MRI machine also results in slightly different positioning of the skeleton relative to soft tissue. However, even this limited validation would improve the confidence with which results can be reported.

As discussed in Chapter 6, the PIG model used to calculate the kinematic and kinetic parameters for analysis had to use estimates for the essential thigh and tibia markers. The comparison of the knee kinematics for the PIG model versus the G&S convention demonstrate the limitations of these estimates, though the parameters at leading leg strike appeared to be comparable.

One of the significant results was seen for the knee abduction/adduction moment at leading leg strike. Previous validation work has shown that for motion capture analysis, the rotation and abduction angles, and therefore the rotation and abduction moments calculated using these angles, have the largest experimental errors, at 4.2 and 5.0 degrees, respectively (194). The experimental error can limit the reliability of the abduction moment. These errors are largely attributed to "cross talk" resulting from misaligned knee markers. Cross talk is most noticeable during large knee flexion angles, and is minimized when the knee is fully extended. For this study, the time point of leading leg foot strike provided a point of large knee extension, so the cross talk effect was expected to be minimized. Therefore, while the rotation and abduction angles may still have the largest experimental errors, the moments calculated using these angles are expected to be acceptable.

The bowling trial selection was based on force plate strike and ball speed. As only one trial for each player was analysed, the assumption was made that analysed trials were representative of each bowler's typical bowling kinematics and kinetics. Only regular or "maximum effort" bowls were used. While centre of mass speed was not found to be significantly different between trials of the same player, similar comparisons were not made for the knee kinematics. Most players had incomplete marker data for a critical marker required for knee kinematics, so the assumption that the bowling action was repeatable was not tested beyond the centre of mass speed.

The biomechanics analysis did not allow for compartment-specific metrics. As noted in the discussion of kinetic results, this limited the conclusions that could be drawn about how each compartment related to loading patterns. The external moments experienced

by each compartment may have been more closely associated with the cartilage morphology, but such a hypothesis could not be tested given this study's data.

Finally, the sample size was small, though it was comparable to other studies of elite athletes and cartilage morphology (82,84). Especially for the lateral tibia compartment results, which had only 8 participants, a small sample size increases the likelihood of type I error, or a detected effect where none exists. However, even with the small sample size, the linear regression models using lateral tibia compartment measurements met the required assumptions and yielded a significant effect.

8.5 Conclusion

This study investigated the relationship between normalised tibial cartilage measurements and the external knee angles and moments experienced by the leading leg during the delivery stride of fast bowling. A significant association was seen between the normalised lateral tibia cartilage measurement and the external knee flexion/extension and abduction/adduction moments at leading leg strike of the delivery stride. No association was seen between the cartilage measurements and knee angles at leading leg strike. The previous chapter found no statistically significant difference between compartmental cartilage volumes of the leading and trailing legs of these fast bowlers but found a clinically significantly greater cartilage measurement in the lateral tibial cartilage of the leading than the trailing leg. This chapter suggests that the cartilage in the lateral tibia compartment is associated with certain external knee moments at leading leg strike. This supports the hypothesis that knee cartilage demonstrates some level of sensitivity to mechanical loads. Future studies should investigate larger sample sizes of elite bowlers to increase the power of results, and should use marker sets and analysis methods that allow for compartment-specific moments in the knee. Such an approach would allow for a more specific analysis of the effect of loading on cartilage morphology.

Chapter 9 Conclusions and Future Work

9.1 Principle Findings

This thesis contributes novel findings towards understanding the short- and long-term effects of elite cricket on health.

A cross-sectional retrospective questionnaire study was designed to address the first and second objectives of this thesis: (1) To define and compare the rates of chronic conditions in a sample of former elite cricketers to those of a general population sample, and (2) To define the prevalence of joint pain, OA, and joint replacement in a sample of former elite cricketers, and to explore the association of injury and cricket-related factors with these outcomes. A cricket-specific questionnaire was developed and the largest cross-sectional cohort of former elite cricketers for the investigation of long-term health outcomes was recruited.

The sample of male former elite cricketers aged 50 and above had significantly lower rates of heart problems and non-significant but lower trending rates of high blood pressure and diabetes than the general population sample. These former cricketers also had higher rates of OA, THR, TKR, anxiety and depression than the general population sample. Over 97% of former cricketers, though, agreed with the statement that they would "do the same again" with regards to their cricket career.

Further investigation of the former elite cricketers explored cricket-related risk factors for OA outcomes of NHANES pain, GP-diagnosed OA, and joint replacement in the former elite cricketers. Joint injury was found to be the strongest predictor of OA outcomes in most joints. No other cricket-related risk factors were significantly associated with OA outcomes. These results support the hypothesis that the increased

risk of OA seen in elite athletes is due to the increased risk of injury in elite sport, rather than other sport-specific factors.

Cross-sectional MRI and biomechanics studies were designed to address the third and fourth objectives of this thesis: (3) To assess the effect of elite fast bowling loads on knee cartilage volume in the leading versus trailing legs, as a potential mechanism for OA, and (4) To test the sensitivity of cartilage to loading conditions by evaluating the associations of kinematic and kinetic parameters during the bowling action with knee cartilage volume. These studies recruited current elite fast bowlers for the first investigation of the effects of a regular load differential between legs on *in vivo* knee cartilage morphology, and of the association of biomechanics parameters from the bowling action with cartilage volume.

The sample of male and female current elite fast bowlers did not demonstrate a statistically significant difference between the compartmental cartilage volumes of the trailing versus the higher loaded leading leg. However, a clinically significantly greater cartilage volume was found in the lateral tibia compartment of the higher loaded leading leg compared to the trailing leg in the total sample. This clinically significant result supports the hypothesis that cartilage volume increases in response to increased loading. A clinically significantly lesser cartilage volume was found in the medial tibia compartment of the higher loaded leading leg compared to the trailing leg in the female bowlers. It was hypothesized that this was due to deleterious loading of the medial compartment compared to the lateral compartment of the female bowlers. The medial tibia compartment result in the female bowlers was consistent with the higher prevalence of pain and OA in the leading leg of former elite bowlers in the former cricketer study.

Further investigation of the current elite fast bowlers found a significant association between the normalised lateral tibia cartilage measurement and the external knee

flexion/extension and abduction/adduction moments at leading leg strike of the delivery stride. This result supports the hypothesis that knee cartilage exhibits sensitivity to mechanical loads. Combined with the clinically significant result from the MRI study, the biomechanics study suggests that the greater lateral tibia cartilage in the leading leg is associated with the loading of the delivery stride.

This thesis has used samples of current and former elite cricketers to investigate short- and long-term health effects of elite cricket. Study of the former elite cricketers has provided targets for injury prevention for current elite cricketers in order to mitigate the risk of developing NHANES pain and OA. Results from the former cricketer study have also identified targets for resource provision for elite cricketers transitioning out of elite sport and for former elite cricketers, in order to prevent chronic conditions that were found to be higher in former elite cricketers than the general population. The results from the study of current elite fast bowlers have demonstrated that elite fast bowlers provide an excellent *in vivo* model to investigate the mechanosensitivity of cartilage. This model can be replicated and not only be relevant for cricketers, but can also improve the understanding of cartilage biomechanics *in vivo*.

9.2 Future Work

The results of this thesis provide opportunity for further research. The results of the former cricketer study provided targets for intervention and prevention in current elite cricketers and cricketers transitioning out of elite sport, particularly the targets of mental and MSK health. Future research should identify interventions and assess the efficacy of resource provision for these conditions through a longitudinal study of elite cricketers.

The identification of joint injury as a key risk factor for long-term OA outcomes in the former elite cricketers provides an opportunity to identify and trial injury prevention

techniques in current cricketers. Future work may focus on injury prevention and rehabilitation of knee injuries in particular, as OA outcomes in the former cricketers were most prevalent at the knee.

The clinically significant results of the MRI study warrant further research of knee cartilage morphology in a larger sample of elite fast bowlers. Future work on bowler cartilage morphology should also utilise semi-automated or automated segmentation, and should recruit inactive controls. If the clinically significant results found in the lateral tibia compartment of the bowlers can be replicated, such work could provide further evidence for encouraging physical activity in adolescents and young adults in order to maximize cartilage volume accrual, and to motivate investigation into whether increased cartilage volume accrual in adolescence protects against future OA.

The significant association of lateral tibia cartilage with kinetic factors also supports further similar research in a larger sample of elite bowlers. Future work should use marker sets and analysis methods that allow for compartment-specific moments or contact forces in the knee. This additional information would allow for a more specific analysis of the effect of loading on cartilage morphology.

Appendix A: Sample PPI Topic Guide

Botnar Research Centre, Oxford **18/2/15**

Focus Group Topic Guide

AN ANALYSIS OF LONG-TERM HEALTH OUTCOMES IN RETIRED CRICKETERS

Introduction (~5 minutes)

- Welcome – thank you for agreeing to participate
- Explanation of the study/questionnaire
- Explanation of PPI and the focus group
    - Organised to receive feedback and player input on our questionnaire
    - The information and feedback we get from this session will be used to inform and amend the questionnaire – with the aim of improving the overall quality and relevance of the research
- Informal and open forum for discussion, no right or wrong views
- Audio recording completely anonymous
- Data protection
    - The recording will be for internal use only (will not be disseminated outside this study)
    - It will only be retained until it is transcribed. The transcription will be anonymised and kept for the purposes of Betsy's DPhil
- Round of introduction – name, primary position

Paper format Questionnaire (~20 minutes)

- Distribute questionnaire
- The questionnaire is designed to be used on the online platform which is much more user-friendly, however it is not currently ready
- Let players provide initial thoughts/feedback
- **What do you think the questionnaire is about?**
- Is the questionnaire understandable?
    - Browse the questions, do any stand out as unclear or incomplete?
        - Any additional sports to add just before current pains?
        - Any other levels of play or K11?
- What are your thoughts on the wording of the questions? Try to cover each section of the questionnaire
    - Are they clear?
    - Do they lead to the answers you think we might want?
- Do you think players would be biased towards over- or under-reporting for any of the questions?
- Are there any questions which you would feel uncomfortable answering?
- Are there any topics which you would not want to discuss surrounding playing?
- Are there any elements of the questionnaire that you feel are ambiguous/could be open to interpretation?

  - K3, "first competitive match"
  - K7, age up to 16 for "youth"

Concussion (~10 minutes)

- Motivated by ECB, suspects underestimates in documented concussion
- K17 – K106
- Any problems with the phrasing or layout of the questions? (is "dazed" sufficient? "knocked out" for concussed?)
- What do you feel would be the best way to structure these questions to scope the incidence and severity of self-reported concussion?
- Do you think there will be differences between retired and current players in terms of their answers to these questions on concussion?
- Is there anything else you think we should add? (ie getting hit by the bat vs the ball?)

Injury/Other (~10 minutes)

- Is there any particular injury not included that you feel should be?
- Have we missed a crucial joint or missed detail into a particular joint?
- Necessary to separate fingers from hand/wrist injuries?
- Relevant to ask about infield vs outfield fielders?
- Any other distinctions within players we should be looking at?
- Current players mentioned they use other sports (football, rugby, etc) for warm up. Do you think this is standard?
  - How would you classify an injury incurred during this activity? (as "cricket" or "football"?)

Well-being (~10 minutes)

- Obviously any sport comes with risk of injury or ill effects. We'd like to also capture the benefits of cricket
- Even if players become injured, what about this sport do you think keeps them coming back to train/play/compete?
- Show them the working questions for well-being, gain initial thoughts
- Do you think players would be comfortable answering these questions?
- Of the last 2 questions ("enriched" vs "how you feel toward your career"), which do you think would best capture the well-being of ex-players?
- Do you think any options are better than others? Are there options missing?

Research Methods (~5 minutes)

- If I didn't know you, what would be the best way of contacting you?
- What would increase the likelihood of you replying to the questionnaire? (timing of distribution, method, incentives/motivation)

Closure (~5 minutes)

- Do you have any questions?
- Would you be available to possibly provide input at a later stage of the project?

Appendix B: Former Cricketer Questionnaire

Cricket Study Questionnaire

Thank you for agreeing to complete this questionnaire. Please ensure you have completed the enclosed consent form. For open text boxes please write your answer on the right. For multiple choice answers, please tick the box to the right of the answer, to indicate which response is most relevant to you.

1. Registration	
1.1. First Name:	
1.2. Surname:	
1.3. Email Address:	

2. Personal Details: We request these details as they may relate to risk of developing osteoarthritis													
2.1. Gender:	Male				Female								
2.2. Year of Birth:	YYYY												
2.3. Weight:	Kg				Stones				Pounds			Don't know	
2.4. Height:	Cm				Feet				Inches			Don't know	
2.5. Do you smoke?	Yes		No						Ex-smoker			Don't know	
2.6. What is your current marital status?					Married				Widowed			Divorced	
Separated		Never married			Long-term relationship				Other			Don't know	
2.7. Please select the ethnicity that is most applicable to you:													
White		Mixed			Black				Asian			Other	
Do not wish to answer					Don't know								

3. Joint Pain: We are interested in understanding how common joint pain is in cricketers													
Hip:													
3.1. Do you experience pain, discomfort, or have a problem with your hip(s) or groin?													
Yes			No								Don't know		
3.2. If yes, have you had to alter your activities as a result of this hip or groin pain?													
Yes			No								Don't know		
3.3. Have you had any pain in your hip(s) or groin on most days of the last month?													
Yes			No								Don't know		
3.4. If yes, which side has this hip or groin pain been on?	Left		Right		Both		Don't know						
3.5. If yes, when does this hip or groin pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know						
3.6. Do you currently have any pain in your hip(s) or groin?	Yes		No		Don't know								
3.7. If yes, which side is this hip or groin pain on?	Left		Right		Both		Don't know						
Knee:													

3.8. Do you experience pain, discomfort, or have a problem with your knee(s)?							
Yes		No		Don't know			
3.9. If yes, have you had to alter your activities as a result of this knee pain?							
Yes		No		Don't know			
3.10. Have you had any pain in your knee(s) on most days of the last month?							
Yes		No		Don't know			
3.11. If yes, which side has this knee pain been on?	Left		Right		Both		Don't know
3.12. If yes, when does this knee pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know
3.13. Do you currently have any pain in your knee(s)?	Yes		No		Don't know		
3.14. If yes, which side is this knee pain on?	Left		Right		Both		Don't know
3.15. Have you **ever** had pain in or around your knee(s)s for **most days over a 3-month period?**	Yes		No		Don't know		
Ankle:							
3.16. Do you experience pain, discomfort, or have a problem with your ankle(s)?							
Yes		No		Don't know			
3.17. If yes, have you had to alter your activities as a result of this ankle pain?							
Yes		No		Don't know			
3.18. Have you had any pain in your ankle(s) on most days of the last month?							
Yes		No		Don't know			
3.19. If yes, which side has this ankle pain been on?	Left		Right		Both		Don't know
3.20. If yes, when does this ankle pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know
3.21. Do you currently have any pain in your ankle(s)?	Yes		No		Don't know		
3.22. If yes, which side is this ankle pain on?	Left		Right		Both		Don't know
Spine:							
3.23. Do you experience pain, discomfort, or have a problem with your spine (back or neck)?							
Yes		No		Don't know			
3.24. If yes, have you had to alter your activities as a result of this spinal pain?							
Yes		No		Don't know			
3.25. Have you had any pain in your cervical spine (neck) on most days of the last month?							
Yes		No		Don't know			
3.26. Have you had any pain in your thoracic spine (mid-back) on most days of the last month?							
Yes		No		Don't know			
3.27. Have you had any pain in your lumbar spine (lower back) on most days of the last month?							
Yes		No		Don't know			
3.28. If yes to 3.25, 26, or 27, when does this spinal pain occur? (please tick all that apply)							
At rest		During exercise		After exercise		Don't know	
3.29. Do you currently have any pain in your spine?	Yes		No		Don't know		
3.30. If yes, which part of your spine is this pain on? (please tick all that apply)							
Cervical (neck)		Thoracic (mid-back)		Lumbar (lower back)		Don't know	
Shoulder:							
3.31. Do you experience pain, discomfort, or have a problem with your shoulder(s)?							
Yes		No		Don't know			
3.32. If yes, have you had to alter your activities as a result of this shoulder pain?							
Yes		No		Don't know			

3.33. Have you had any pain in your shoulder(s) on most days of the last month?											
Yes		No						Don't know			
3.34. If yes, which side has this shoulder pain been on?	Left		Right		Both		Don't know				
3.35. If yes, when does this shoulder pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know				
3.36. Do you currently have any pain in your shoulder(s)?	Yes		No		Don't know						
3.37. If yes, which side is this shoulder pain on?	Left		Right		Both		Don't know				
Elbow:											
3.38. Do you experience pain, discomfort, or have a problem with your elbow(s)?											
Yes		No						Don't know			
3.39. If yes, have you had to alter your activities as a result of this elbow pain?											
Yes		No						Don't know			
3.40. Have you had any pain in your elbow(s) on most days of the last month?											
Yes		No						Don't know			
3.41. If yes, which side has this elbow pain been on?	Left		Right		Both		Don't know				
3.42. If yes, when does this elbow pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know				
3.43. Do you currently have any pain in your elbow(s)?	Yes		No		Don't know						
3.44. If yes, which side is this elbow pain on?	Left		Right		Both		Don't know				
Fingers / Hand:											
3.45. Do you experience pain, discomfort, or have a problem with your finger(s) / hand(s)?											
Yes		No						Don't know			
3.46. If yes, have you had to alter your activities as a result of this finger / hand pain?											
Yes		No						Don't know			
3.47. Have you had any pain in your finger(s) / hand(s) on most days of the last month?											
Yes		No						Don't know			
3.48. If yes, which side has this finger / hand pain been on?	Left		Right		Both		Don't know				
3.49. If yes, when does this finger / hand pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know				
3.50. Do you currently have any pain in your finger(s) / hand(s)?	Yes		No		Don't know						
3.51. If yes, which side is this finger / hand pain on?	Left		Right		Both		Don't know				
Wrist:											
3.52. Do you experience pain, discomfort, or have a problem with your wrist(s)?											
Yes		No						Don't know			
3.53. If yes, have you had to alter your activities as a result of this wrist pain?											
Yes		No						Don't know			
3.54. Have you had any pain in your wrist(s) on most days of the last month?											
Yes		No						Don't know			
3.55. If yes, which side has this wrist pain been on?	Left		Right		Both		Don't know				
3.56. If yes, when does this wrist pain occur? (please tick all that apply)	At rest		During exercise		After exercise		Don't know				

3.57. Do you currently have any pain in your wrist(s)?			Yes		No		Don't know	
3.58. If yes, which side is this wrist pain on?	Left		Right		Both		Don't know	
Osteoarthritis:								
3.59. Have you ever been told by a Doctor that you have Osteoarthritis?			Yes		No		Don't know	

4. Playing History: We are interested in how your sporting career may relate to your current health. Please note, if you were not a "professional", please read this term as the period of your career that you played for a First Class County.												
4.1. Playing status	Currently playing		Ex-player		Don't know							
4.2. Date of retirement from cricket:	MM/YYYY		Currently playing "professionally"		Don't know							
4.3. If you are retired from cricket, reason for retirement from cricket:												
Cricket related injury		Contract not renewed		Personal reasons								
Age		Non-cricket related injury		Other, please specify:								
Chronic pain		My terms/My choice										
4.4. Approximately how many matches did you play after you retired from "professional" cricket?												
				Don't know								
4.5. Are you right handed, left handed or both?	Left		Right		Both		Don't know					
4.6. Are you right footed, left footed or both?	Left		Right		Both		Don't know					
4.7. When you bowl or throw, were/are you left handed or right handed?	Left		Right		Don't know							
4.8. When you bat, were/are you left handed or right handed?	Left		Right		Don't know							
4.9. Age at first "schoolboy" or casual game:					Don't know							
4.10. Age that you joined your first adult team:					Don't know							
4.11. Age that your first "professional" contract started, or, if you were not a "professional," age that you started playing cricket for a first class County:					Don't know							
4.12. Predominant position of play as a youth (up to age 16):												
Spin Bowler		Medium Pace Bowler		Fast-Medium Bowler		Fast Bowler						
All-rounder / Spin Bowler		All-rounder / Medium Pace Bowler		All-rounder / Fast-Medium Bowler		All-rounder / Fast Bowler						
Batsman		Wicketkeeper		Wicketkeeper / Batsman		Don't know						
4.13. Predominant position of play as a player (after age 16):												
Spin Bowler		Medium Pace Bowler		Fast-Medium Bowler		Fast Bowler						
All-rounder / Spin Bowler		All-rounder / Medium Pace		All-rounder / Fast-Medium Bowler		All-rounder /						

		Bowler				Fast Bowler	
Batsman		Wicketkeeper		Wicketkeeper / Batsman		Don't know	
4.14. If your predominant playing position is/was not as a bowler or bowling all-rounder, at what age did you stop bowling?						Don't know	
4.15. Can you try and estimate how many overs per season you bowled as a "professional"?						Don't know	
4.16. If you had to choose one position which was your predominant fielding position:		Inner-ring				Boundary	
		Close Catcher				Don't know	
4.17. At what standard did you compete for the **majority** of your playing career?							
International		County				Other First Class	
Club		Other, please specify:				Don't know	
4.18. For how many seasons did you play at this level?						Don't know	
4.19. What was your **highest** level of play?							
International		County				Other First Class	
Other, please specify:						Don't know	
4.20. For how many seasons did you play at your highest level?						Don't know	
4.21. Approximately how many of the following matches did you take part in at your highest level?							
Test Match		Twenty20		One day match			
3- or 4-Day Games				Don't know			
4.22. How many "professional" seasons did you play in the UK?						Don't know	
4.23. How many "professional" seasons did you play abroad?						Don't know	
4.24. How many "professional" seasons were you unable to complete due to injury?						Don't know	
4.25. Approximately how many matches did you take part in during your "professional" career?							
						Don't know	
4.26. Have you **mostly** played at an amateur or "professional" level?							
Amateur		Professional				Don't know	
4.27. Average weight during adult playing career:							
Kg		Stones		Pounds		Don't know	
On average, how many hours per day and days per week have you spent training during the following periods? Please include all sport and exercise, not just cricket.							
4.28. As a youth (up to age 16)?		Hours per day _____ Days per week _____				Don't know	
4.29. As a player (after age 16)?		Hours per day _____ Days per week _____				Don't know	
4.30. Currently?		Hours per day _____ Days per week _____				Don't know	
Did you play any of the following sports competitively before or during your "professional" cricket:							
4.31. **Football**		Yes		No		Don't know	
4.32. If yes, how many seasons did you play at each of the following levels?						Recreational	
Club		Representative (some selection)		International		Don't know	
4.33. **Rugby**		Yes		No		Don't know	
4.34. If yes, how many seasons did you play at each of the following levels?						Recreational	
Club		Representative (some selection)		International		Don't know	
4.35. **Hockey**		Yes		No		Don't know	
4.36. If yes, how many seasons did you play at each of the following levels?						Recreational	
Club		Representative (some selection)		International		Don't know	

4.37. **Athletics / Track & Field**	Yes		No		Don't know		
4.38. If yes, how many seasons did you play at each of the following levels?					Recreational		
Club		Representative (some selection)		International		Don't know	
4.39. **Golf**	Yes		No		Don't know		
4.40. If yes, how many seasons did you play at each of the following levels?					Recreational		
Club		Representative (some selection)		International		Don't know	
4.41. **Rowing**	Yes		No		Don't know		
4.42. If yes, how many seasons did you play at each of the following levels?					Recreational		
Club		Representative (some selection)		International		Don't know	
4.43. **Cycling**	Yes		No		Don't know		
4.44. If yes, how many seasons did you play at each of the following levels?					Recreational		
Club		Representative (some selection)		International		Don't know	
4.45. **Other sport (not mentioned above), please specify:**	Yes		No		Don't know		
4.46. If yes, how many seasons did you play this sport at each of the following levels?					Recreational		
Club		Representative (some selection)		International		Don't know	

5. Medical History: We request these details as they may relate to outcomes we want to understand. If you are unsure about or unfamiliar with a term, you may provide your best answer or "Don't know"									
5.1. During your teenage years, did you physically develop earlier, on average, or later compared to your peers?	Early		Average		Late		Don't know		
Have you ever been told you have any of the following by a Doctor?									
5.2. Asthma	Yes		No		Don't know				
5.3. Diabetes	Yes		No		Don't know				
5.4. Dementia	Yes		No		Don't know				
5.5. Epilepsy	Yes		No		Don't know				
5.6. High blood pressure	Yes		No		Don't know				
5.7. Depression	Yes		No		Don't know				
5.8. Heart problems (e.g. heart attack or angina)	Yes		No		Don't know				
5.9. Stroke	Yes		No		Don't know				
5.10. Osteoporosis	Yes		No		Don't know				
5.11. Anxiety	Yes		No		Don't know				
5.12. Kidney problems	Yes		No		Don't know				
5.13. Memory impairment	Yes		No		Don't know				
5.14. Any other medical problems?	Yes		No		Don't know				
5.15. If yes, please give details:									
5.16. Have you ever had a slipped growth plate (SUFE) in your hip, Perthes' Disease or Avascular Necrosis?									
Yes		No		Don't know					
5.17. If yes, which side?	Left		Right		Both		Don't know		
5.18. Did you ever have clicking hips, dislocated hips or hip dysplasia at birth?									
Yes		No		Don't know					
5.19. If yes, which side?	Left		Right		Both		Don't know		
5.20. Have you ever had inflammatory Arthritis (Rheumatoid Arthritis, Ankylosing Spondylitis, Psoriatic Arthritis, Juvenile Idiopathic Arthritis)?									
Yes		No		Don't know					

5.21. Have you ever been told you have wear and tear, degeneration or Osteoarthritis by a Doctor?					
Yes		No (Continue to 5.24)		Don't know	

5.22. If yes, where? Please circle all the joint(s)/side(s) involved and also specify "other" if necessary:												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.23. If yes, please indicate at what age you were told this, below the affected joint(s)/side(s):												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.24. Have you ever had keyhole surgery / arthroscopy?					
Yes		No (Continue to 5.26)		Don't know	

5.25. If yes, where? Please also indicate the number for each joint/side:												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.26. Have you ever had joint replacement surgery?					
Yes		No (Continue to 5.29)		Don't know	

5.27. If yes, where? Please also indicate the number for each joint/side:												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.28. If yes, please indicate the age you were when you had this surgery, below the affected joint(s)/side(s):												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.29. Have you ever had any broken bones or fractures?					
Yes		No		Don't know	

5.30. If yes, where? Please also indicate the number for each joint/side:												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

5.31. If yes, please write 'C' if you had any broken bones or fractures that were cricket related, or 'NC' for non-cricket related, below each affected joint/side:												
Hip		Knee		Ankle		Shoulder		Wrist		Hand		Other joint:
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

6. Past injuries: We are interested in how past injuries relate to current joint health					
6.1. Have you ever had any injuries leading to more than 4 weeks of reduced participation in exercise, training or sport?					
Yes		No		Don't know	
6.2. Have you ever had any injuries in your **spine**, leading to more than 4 weeks of reduced participation in exercise, training or sport?					
Yes		No (Continue to 6.7)		Don't know	
6.3. If yes, which part of the spine was affected? Please select all that apply.					
Neck (cervical spine)		Mid-back (thoracic spine)		Lower back (lumbar spine)	
6.4. If yes, how many spine injuries?					
Neck (cervical spine)		Mid-back (thoracic spine)		Lower back (lumbar spine)	

6.5. If yes, how many of each of the following types of spine injuries have you had? Please specify.									
Fracture		Prolapsed disc							
Facet Joint Problem		Other, please specify type and number:							
Sciatica									
6.6. If yes, how many of these spine injuries were cricket or non-cricket related?									
Training		Playing		Warming up		Non-cricket related		Don't know	
6.7. Have you ever had any injuries in your **shoulder(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?									
Yes		No (Continue to 6.11)						Don't know	
6.8. If yes, how many shoulder injuries?		Left:		Right:				Don't know	
6.9. If yes, how many of each of the following types of shoulder injuries have you had? Please specify.									
Fracture		Dislocation		Muscle tear / strain					
Tendinopathy		Other, please specify type and number:							
6.10. If yes, how many of these shoulder injuries were cricket or non-cricket related?									
Training		Playing		Warming up		Non-cricket related		Don't know	
6.11. Have you ever had any injuries in your **elbow(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?									
Yes		No (Continue to 6.15)						Don't know	
6.12. If yes, how many elbow injuries?		Left:		Right:				Don't know	
6.13. If yes, how many of each of the following types of elbow injuries have you had? Please specify.									
Fracture		Dislocation		Muscle tear / strain		Tendinopathy			
Epicondylitis (tennis/golfer's elbow)		Other, please specify type and number:							
6.14. If yes, how many of these elbow injuries were cricket or non-cricket related?									
Training		Playing		Warming up		Non-cricket related		Don't know	
6.15. Have you ever had any injuries in your **finger(s) / hand(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?									
Yes		No (Continue to 6.19)						Don't know	
6.16. If yes, how many finger / hand injuries?		Left:		Right:		Don't know			
6.17. If yes, how many of each of the following types of finger / hand injuries have you had? Please specify.									
Fracture		Dislocation		Ruptured ligament					
Other, please specify type and number:									
6.18. If yes, how many of these finger / hand injuries were cricket or non-cricket related?									
Training		Playing		Warming up		Non-cricket related		Don't know	
6.19. Have you ever had any injuries in your **wrist(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?									
Yes		No (Continue to 6.23)						Don't know	
6.20. If yes, how many wrist injuries?		Left:		Right:				Don't know	
6.21. If yes, how many of each of the following types of wrist injuries have you had? Please specify.									
Fracture		Tendinopathy		Muscle tear / strain					
Carpal tunnel syndrome (causes pain, numbness, and tingling in hands and fingers)									
Other, please specify type and number:									
6.22. If yes, how many of these wrist injuries were cricket or non-cricket related?									
Training		Playing		Warming up		Non-cricket related		Don't know	
6.23. Have you ever had any injuries in your **hip(s) or groin**, leading to more than 4 weeks of reduced participation in exercise, training or sport?									
Yes		No (Continue to 6.27)						Don't know	

6.24. If yes, how many hip or groin injuries?		Left:		Right:		Don't know					
6.25. If yes, how many of each of the following types of hip or groin injuries have you had? Please specify.											
Fracture		Stress Fracture		Impingement							
Hernia		Gilmore's groin (sports hernia)		Adductor muscle injury							
Other, please specify type and number:											
6.26. If yes, how many of these hip or groin injuries were cricket or non-cricket related?											
Training		Playing		Warming up		Non-cricket related		Don't know			
6.27. Have you ever had any injuries in your **knee(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?											
Yes		No (Continue to 6.31)				Don't know					
6.28. If yes, how many knee injuries?		Left:		Right:		Don't know					
6.29. If yes, how many of each of the following types of knee injuries have you had? Please specify.											
Meniscus injury				Patellar tendinopathy							
Anterior cruciate ligament (ACL) injury				Other, please specify type and number:							
Medial collateral ligament (MCL) injury											
Lateral collateral ligament (LCL) injury											
6.30. If yes, how many of these knee injuries were cricket or non-cricket related?											
Training		Playing		Warming up		Non-cricket related		Don't know			
6.31. Have you ever had a significant cricket-related **knee** injury, which has caused you pain for most days during a 3-month period and resulted in an absence from all training and matches during this time?											
Yes		No (Continue to 6.33)				Don't know					
6.32. If yes, please specify the number of significant (as above) cricket-related injuries you have had in your left knee and right knee:											
Left knee:		Don't know		Right knee:		Don't know					
6.33. Have you ever had any injuries in your **ankle(s)**, leading to more than 4 weeks of reduced participation in exercise, training or sport?											
Yes		No (Continue to 6.37)				Don't know					
6.34. If yes, how many ankle injuries?		Left:		Right:		Don't know					
6.35. If yes, how many of each of the following types of ankle injuries have you had? Please specify.											
Fracture		Achilles tendinopathy				Ankle sprain					
Other, please specify type and number:											
6.36. If yes, how many of these ankle injuries were cricket or non-cricket related?											
Training		Playing		Warming up		Non-cricket related		Don't know			
6.37. Have you ever been concussed while playing cricket?	Yes		No (Continue to Section 7)			Don't know					
6.38. If yes, how many times have you been concussed while playing cricket?						Don't know					
6.39. If yes, during how many of these concussions were you wearing a helmet at the time?						Don't know					
6.40. If yes, did any of these concussions occur during a match or training? (please tick all that apply)	Match		Training		Don't know						
6.41. Of the concussions that occurred during a match, how many occurred during the following activities? Please specify.											
Batting		Fielding		Collision		Don't know					

6.42. Of the concussions that occurred during training, how many occurred during the following activities? Please specify.							
Batting		Fielding		Collision		Don't know	

7. Family history: We request these details as they may relate to risk of developing osteoarthritis											
Have your parents or any brothers or sisters ever had any of the following?											
7.1. Told by a Doctor that they have wear and tear/degeneration of the joints or been diagnosed with osteoarthritis?											
Yes					No				Don't know		
7.2. If yes, where? Please select all the joints that apply and/or specify "other":											
Hip		Knee		Shoulder		Hand		Other, please specify:		Don't know	
7.3. Joint replacement surgery?											
Yes					No				Don't know		
7.4. If yes, where? Please select all the joints that apply and/or specify "other":											
Hip		Knee		Shoulder		Hand		Other, please specify:		Don't know	

8. Occupation				
8.1. Are you currently employed?	Yes		No	
8.2. If no, are you retired?	Yes		No	
8.3. If employed or retired, what is/was your main occupation?				

9. Wellbeing – for each question, please circle one as appropriate:
9.1. Considering the benefits and risks of my previous participation in cricket, I would do the same again.
1 Strongly agree 2 Agree 3 Undecided 4 Disagree 5 Strongly Disagree
9.2. Considering the benefits and risks of my previous participation in cricket, I would recommend this to my children, relatives or close friends.
1 Strongly agree 2 Agree 3 Undecided 4 Disagree 5 Strongly Disagree
9.3. Did your cricket career enrich your life?
1 Dramatically 2 Somewhat 3 Undecided 4 Not really 5 Not at all
9.4. On average, how many minutes per week do you **currently** spend doing physical activity? Please include all sport and exercise, not just cricket.
_____ minutes per week
9.5. My previous participation in cricket has resulted in an **increase** in my **current** physical activity level.
1 Strongly agree 2 Agree 3 Undecided 4 Disagree 5 Strongly Disagree
9.6. My previous participation in cricket has resulted in a **decrease** in my **current** physical activity level.
1 Strongly agree 2 Agree 3 Undecided 4 Disagree 5 Strongly Disagree

Thank you for your time. Please return the questionnaire in the enclosed envelope.

Appendix C: MRI Study Participant Questionnaire

VOLUNTEER QUESTIONNAIRE
Date and Version No: 17/09/15 Version 1
Title: MRI assessment of knee health of current professional fast bowlers
CUREC Ref: MS-IDREC-C1-2015-189

1	Age:						Don't know	
2	When you bowl or throw, are you left handed or right handed?	Left		Right			Don't know	
3	When you bat, are you left handed or right handed?	Left		Right			Don't know	
4	Age that your first professional contract started:						Don't know	
5	Can you try and estimate how many overs per season you bowled as a professional?						Don't know	
6	Have you ever had any injury in your **knee**, leading to more than 4 weeks of reduced participation in exercise, training or sport?	Yes		No			Don't know	
7	If yes, how many?	Left:		Right:			Don't know	

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

KOOS KNEE SURVEY

Today's date: _____/_____/_____ Date of birth: _____/_____/_____

Name: _____

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms

These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness

The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

Pain

P1. How often do you experience knee pain?

Never ☐ Monthly ☐ Weekly ☐ Daily ☐ Always ☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P3. Straightening knee fully

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P4. Bending knee fully

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P5. Walking on flat surface

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P6. Going up or down stairs

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P7. At night while in bed

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P8. Sitting or lying

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P9. Standing upright

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A2. Ascending stairs

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

Participant ID: _____

Appendix D: Image Analysis Protocol

3D Slicer 4.4 Knee Cartilage Volume Segmentation User Guide

Getting Started:

Open 3D Slicer

Select "Load DICOM Data" in top left

Select file, making sure file is selected in all 3 viewers of DICOM Browser

Click "Load" (Copy files if prompted)

If continuing a previously saved volume:

Select "Load Data" in top left

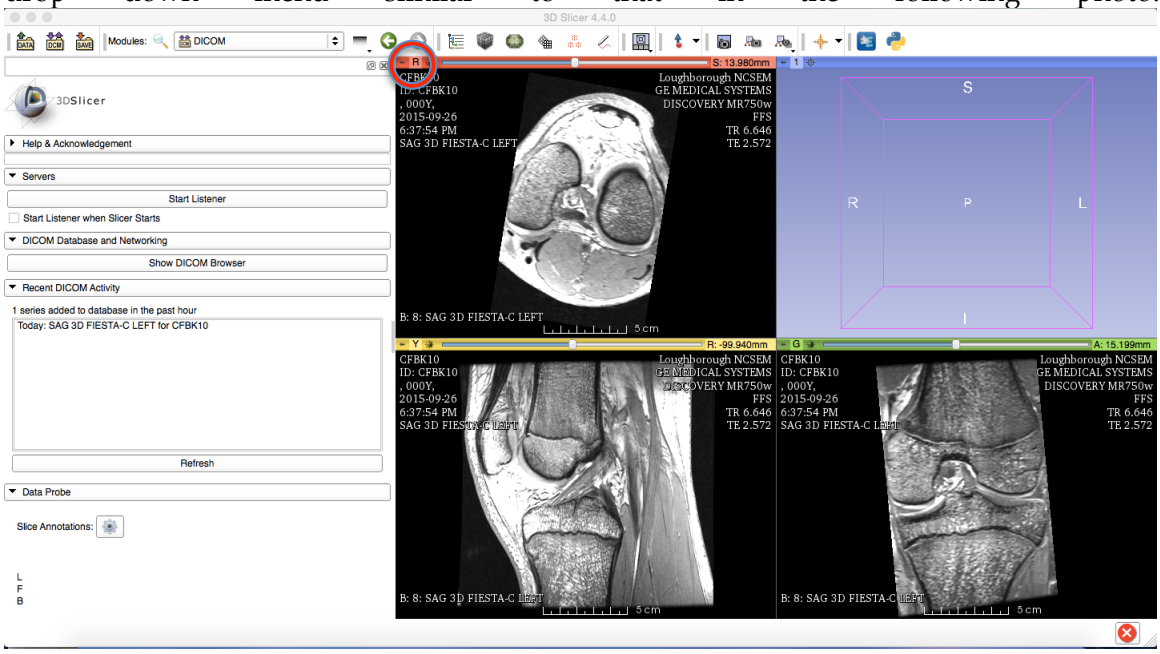
Click "Choose Files to Add"

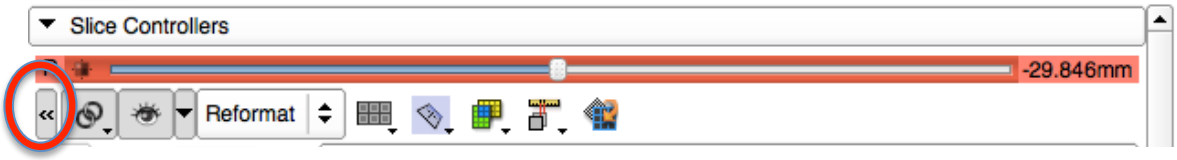
Select file from your documents

Click "OK"

Volume should be added to your loaded scan

Select the small arrows/pin in the top left of the red (axial) view box (circled), to get a drop down menu similar to that in the following photo:



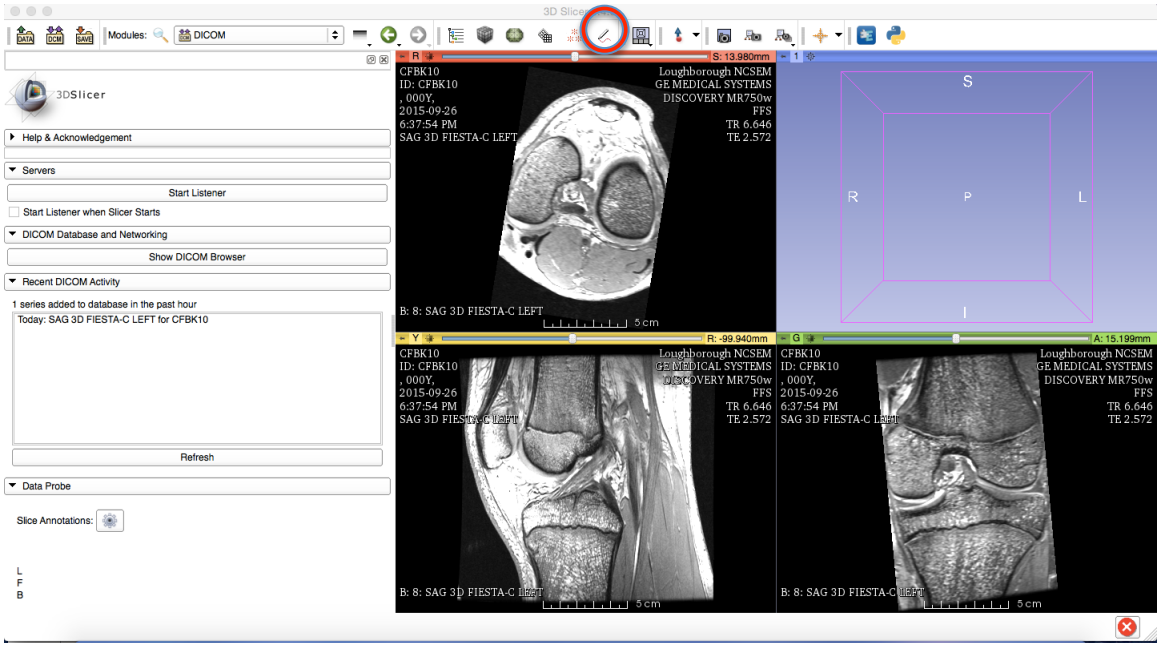


Click the double arrows (circled above) to expand the drop down further.

Link the views, and reset the orthogonality (orientation)

Once the scans are oriented, click the "link slice" icon again to unlink the views.

Now go to the Editor icon at the top of the toolbar (circled below)

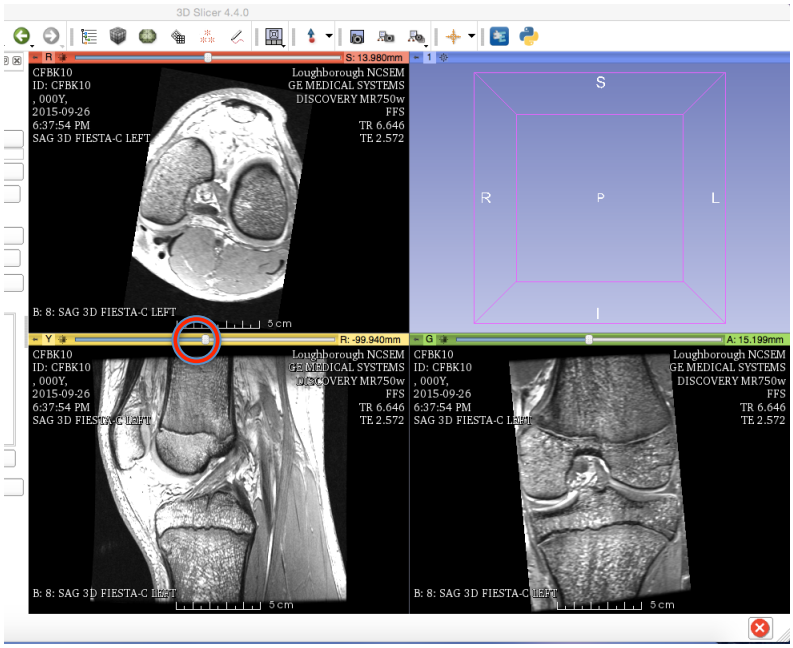


Click "Apply" for "Generic Anatomy Colors"

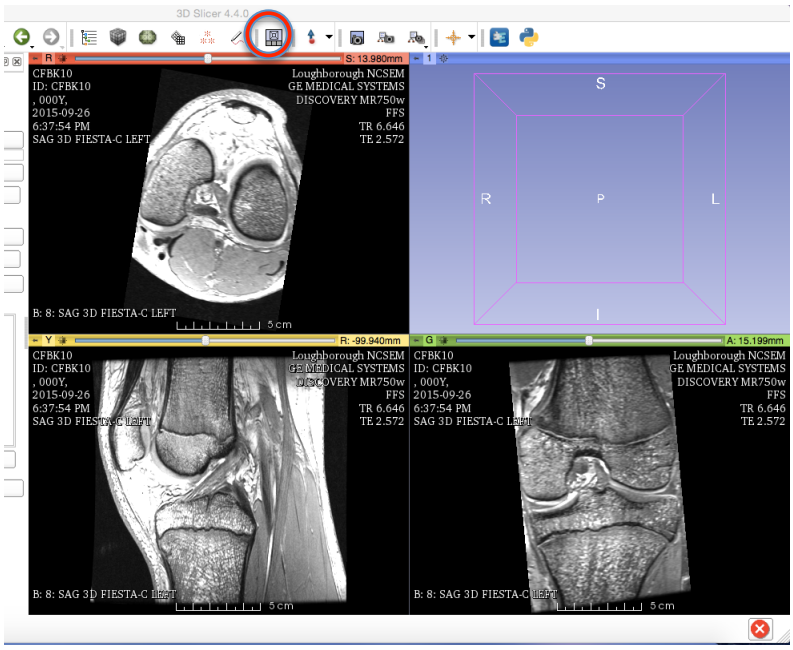
General Navigation:

Using the cursor tool on the scan, left click and drag left to right to change the contrast. Left click and drag up and down to change the brightness so that the region of interest is distinct from surrounding tissue.

To readjust a scan's position on the screen, select the cursor tool. While holding the "Shift" key, left click and drag anywhere on the scan to reposition. Right click and drag down to zoom in, right click and drag up to zoom out. Scroll up and down to change slices, or drag the bar at the top of a window left or right (circled below).

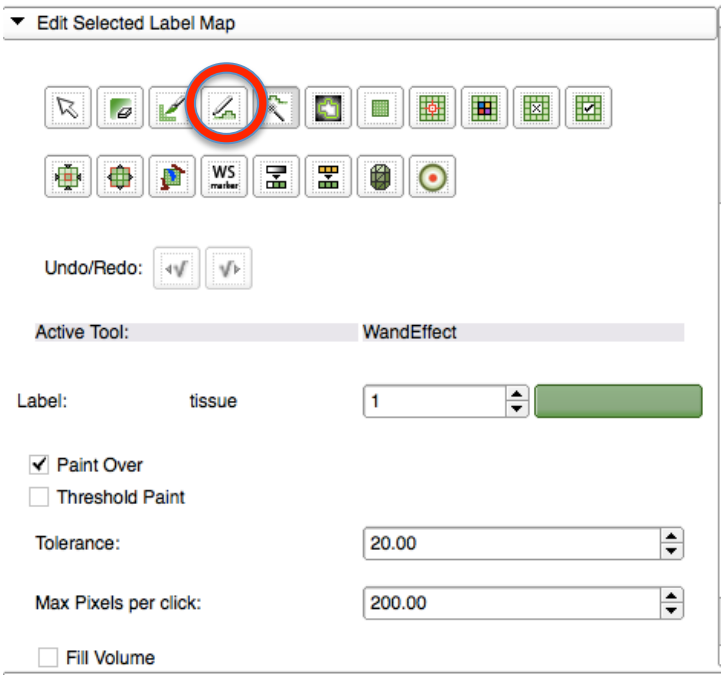


To see only one view (e.g. Red only), click the Change View icon (circled below) and choose the view that's most helpful (Four Up is shown below):

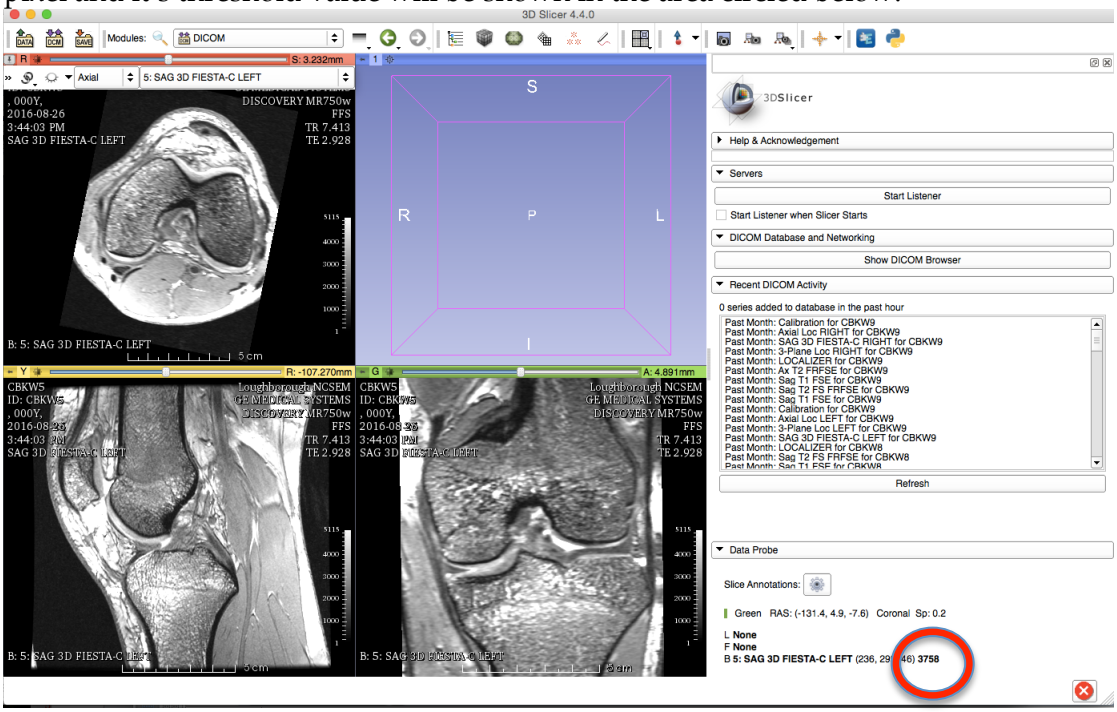


Segmentation:

1. To start a region of interest, first set threshold values. Select the **DrawEffect** tool from the Editor.



2. Check "**Threshold Paint**" and set the threshold values (this will vary by scan, but usually around 2000 min to 7000 – 8000 max). You can hover your mouse over a pixel and it's threshold value will be shown in the area circled below:



3. Select the appropriate label color for the region of interest (15 for patellas, 16 for medial tibia, 17 for lateral tibia)
4. Left click with the **DrawEffect** tool and drag the line around the border of the region of interest, or click around the border.
    a. To undo a click with the DrawEffect tool, press the "X" key on your keyboard.
5. When the region has been encompassed, right click to fill with the appropriate label. Test the threshold for the scan to ensure it is capturing what is intended, and not capturing anything not desired. Trial and error can be used for this.
6. Press the "Z" key to Undo any mistakes. Press "Y" to redo.

7. To erase, either undo with "Z" or use the **DrawEffect** tool with "**0 – background**" Label.
    a. Press the "E" key on your keyboard to toggle between the 0-background label and your selected colour label.
8. **Saving**
    a. To save, click **Save** to generate the **Save Menu**.
    b. Only the .NRRD files will be necessary. They have the label maps and should be overridden as a scan's analysis progresses (.NRRD files with 10 or more numbers after them are not necessary, only the scan name .NRRD file is necessary, e.g. 5-SAG 3D FIESTA-C LEFT)
    c. Select the appropriate **Directory** for the selected files (e.g. MEASUREMENTS/CFBK#)
        i. Ensure the correct participant folder is selected, as there is no other way to ensure the appropriate label map will be used with the correct participant
    d. Click "**Save**".
    e. To pick up with a scan after closing 3D slicer, load the scan DICOM data as above. Then go to "File", "Add Data" to select the nrrd label map file.

For the patella:

Use label 15 for the patellar cartilage. From the sagittal view, it's easiest to start somewhere in the middle of the patellar cartilage, where borders are clear, and work outwards to the edges. Once all sagittal slices have been filled, switch to the axial view and clean the edges, working superior to inferior.

For the tibial compartments:

Use label 16 for the medial tibial plateaus and 17 for lateral tibial plateaus. Start in the coronal view and find the fibula, this is the lateral side. Start segmenting cartilage from the coronal view; it's easiest to start away from the anterior or posterior edges, and work outwards. To clean the edges, switch to the sagittal view. When in doubt about cartilage versus other soft tissue, use the cross hairs (select "**Navigation**", and "**Basic crosshair**") to look at the tissue from the other views.

Shortcuts

"**Z**" to Undo

"**Y**" to Redo

"**E**" to get the background color for erasing (and to go back to the label colour)

"**X**" to Undo a click in the DrawEffect tool

"**B**" and "**F**" to go backwards and forwards between slices

"**D**" to select the DrawEffect tool when the Editor is open

"**Esc**" to select the cursor tool when the Editor is open

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