

# **Quantification of load and lower limb injury in Men's Professional Basketball**

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by

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## **ATTESTATION OF AUTHORSHIP**

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

A handwritten signature in black ink, appearing to read 'Kaitlyn Weiss', with a long horizontal stroke extending to the right.

Kaitlyn Weiss

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## COAUTHORED PAPERS

Chapter publication reference	Author %
CHAPTER 2: Weiss, K., & Whatman, C. (2015). Biomechanics associated with patellofemoral pain and ACL injuries in sports. <i>Sports Medicine</i> .	KW 90% CW 10%.
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Ethical approval for this thesis was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference for this thesis was:

14/383 The use of inertial sensors to monitor biochemical risk factors associated with knee injury in top-level netball. Approved on 15<sup>th</sup> December 2014.

\*Note that subsequent amendments approved by AUTEC allowed for the project to proceed with basketball.

## ABSTRACT

Lower limb injuries are a significant issue in basketball and load has been implicated as a causative factor. The quantification of the training load-injury relationship requires the implementation of effective injury and load monitoring. To set up an effective monitoring system, the efficacy of the methodologies and metrics must first be established. The aim of this thesis was to quantify training load and injuries in professional men's basketball and investigate the relationship between training load and lower limb injuries.

Overuse injuries and load were quantified in professional men's basketball through the use of wearable technology (inertial sensors) and a recently developed overuse injury questionnaire. The magnitude and prevalence of common overuse injuries (ankle, knee, low back) was determined using a self-reporting overuse injury questionnaire. This questionnaire captured many more overuse injuries than standard reporting methods. The prevalence of ankle, knee, and lower back overuse injuries was 13%, 24%, and 26%, respectively (Chapter 4). Lower limb loading was quantified by first monitoring the counts of impacts at low, moderate, and high intensities using wearable accelerometers. Then we incorporated the counts of impacts into an adapted tissue load metric to better quantify external, or mechanical, bilateral lower limb loads (Chapter 5). Findings indicated similar team mean bilateral lower limb load/min between limbs, with variability in the data between individuals and limbs. For several players this load/min metric presented a different picture of load magnitude and symmetry compared to the steps/min measure. Lastly, we investigated the relationship between load and injury. To accomplish this, we first quantified internal load using the session-RPE (session-rate of perceived exertion) method and examined the relationship between this and injury (Chapter 6). The results determined that maintaining acute:chronic workload ratios between 1-1.5 may be optimal for reducing injury in professional basketball players. To further investigate the relationship between load and injury, several methods for quantifying lower limb loads (overuse injury questionnaire, wearable accelerometers, and 3D motion capture) were evaluated together as part of a knee-injury case study. The combination of all three metrics provided the most informative picture of the relationship between load and injury (Chapter 7).

This thesis demonstrated novel methods for quantifying lower limb loads and

injury which can be used for effective monitoring in professional basketball. The objective data collected through the application of these methods may provide beneficial information to help guide best practices with respect to training load, injuries, rehabilitation, and performance outcomes.

# **CHAPTER 1: INTRODUCTION**

## **Rationale**

Basketball is one of the most popular sports in the world, with over 450 million participants worldwide (1). The sport is characterized by a long season consisting of numerous back to back games, travel, and often multiple games played on a weekly basis. Athletes experience tremendous physical demands throughout the course of a game, including quick accelerations and decelerations (2, 3), explosive jumping tasks (2), large eccentric loading (4), high physiological and mechanical loads, and physical contact from other athletes on the court. Time-motion analysis in elite men's basketball has found that players execute between 997 and 1105 movement tasks during a match (5-7), with the time spent at each intensity for these tasks ranging between 50-72%, 17-43%, and 6-20% for low, moderate, and high-intensity tasks respectively (3, 5-7). Thus, the sport is highly intermittent in nature.

Across the various non-contact sports, basketball has been identified as having the highest incidence of injuries (8, 9). Recent research has even noted basketball to have a higher risk of injuries than many contact sports (8, 9). Overuse injuries, where there is no inciting event attributed to the onset of the injury, are considered the primary injury type in sports such as basketball that involve a lot of repetitive jumping and landing (10). The most common injuries in basketball are reported to involve the ankles, knees, and lower back, with knee injuries representing the majority of injuries during practice and in games (11-14). More so than other lower limb injuries, knee injuries such as ACL injury and PFPS are of concern as they continue to impact players throughout their lives. Additionally, injuries to the knee are potentially of most concern as previous research across a number of sports as shown these to have the greatest impact due to time-loss in sport (14, 15). Potential longer term implications of these injuries include increased risk of osteoarthritis and associated increased risk of problems associated with decreased physical activity; and, increased risk of future injury during the athlete's playing career (16, 17).

## **Training loads and injuries**

Training loads in basketball are an important consideration as an injury risk factor (18). The human body is designed to respond and adapt to its loading environment in order to maintain homeostasis. To do this the body must continuously

receive a training stimulus that is sufficient enough to elicit a stable equilibrium. Both under and overloading the body can lead to injuries and negative adaptations. In the context of training loads in basketball, these loads may be physiological, or internal loads as well as mechanical, or external loads (19). With basketball, the heart rate response to a bout of training can be classified as a physiological (internal) load, whereas the impact loads from jumping, landing, running, and sidestepping constitute the mechanical (external) loads acting on the athletes' bodies. The total training load is comprised of both the internal and external load stimuli experienced by the athletes. This training dose-response relationship is based on work by Banister and colleagues (20) where an athlete's performance was estimated by looking at the difference between the negative function (fatigue) and positive function (fitness) resulting from a specific training load stimulus. One current iteration of this model is the acute to chronic workload ratio which looks at the training load performed by an athlete with respect to the load they have prepared for (21). Previous research has found that both high and low training loads lead to increased risk of non-contact musculoskeletal injuries across a variety of sports (19, 22). However, there is a lack of research in professional basketball investigating the relationship between training loads and injury.

In basketball, athletes perform a variety of jumping, landing, running, and change in direction tasks (23). Each time they perform these tasks, mechanical loads are imposed on the body, which can lead to either positive adaptations such as increased structural integrity, or negative adaptations such as an injury. The ligaments, tendons, cartilage, and muscles all work together to maintain structural integrity of the joints over a range of loads. This range of loads has been referred to as the envelope of function (24) and represents the range and frequency of loads that the joints can attenuate while maintaining homeostasis (24). When the musculoskeletal tissue experiences supra-physiological overload (e.g. during pre-season or back to back competitions), structural failure can occur, resulting in injury (24). A number of different factors create this envelope of function including kinematics, anatomy, physiology, and injury. The overall goal is to augment this envelope of function for the athletes' musculoskeletal tissue with the minimum amount of risk (25).

With many of the common musculoskeletal injuries in basketball, the primary cause has been suggested as overuse problems in the lower body (26) (ankles, knees, lower back), which may be due to mechanical loading that falls outside of the envelope of function (27, 28) (i.e. under-loading due to having to decrease basketball training

due to injury; or, overloading such as during pre-season and tournaments). Previous epidemiological research has determined that repetitive loading through either sports or occupation impacts the initiation of degradation of the musculoskeletal tissue/joints (29). This may be due to loading of the tissue outside its envelope of function, increasing the risk of injury (30). These injuries result from stresses being applied to the musculoskeletal system (quantified based on internal and external loads) that exceed the tissue's mechanical strength. The mechanism of tissue failure is related to frequency, magnitude, and rate of loading. During the various landing tasks in basketball, when the athlete's foot makes contact with the ground, a reaction force results in an acceleration wave that moves up through the body (31). When impact accelerations are excessive relative to joint integrity, injuries both acute (ACL) and chronic (PFPS) injuries can result (32, 33). Though the knee joint's structures are able to mitigate some of these impact accelerations (via tendons, cartilage, ligaments, bones), the joint's ability to attenuate these accelerations is predominantly controlled by muscular action and the resultant joint kinematics (34). Cadaver research looking at impact-induced anterior tibial acceleration and resultant ACL strain during simulated single leg landings observed a significant and direct correlation with times to respective peaks for anterior tibial acceleration and anteromedial bundle strain (35).

An additional consideration with respect to the effect of load on musculoskeletal tissue is accumulation of load, which has been cited as a factor in injury risk (36-38). For example, previous research has established cumulative loading as a better predictor than peak loading for low back pain (39). Additionally research looking at cumulative knee loading in healthy and osteoarthritic subjects determined that cumulative knee loading was a better predictor of knee joint degradation than peak loading (40). This was thought to be because it incorporates a broader range of mechanical factors such as knee moment impulse and loading repetition (40). In the context of knee articular cartilage, the mechanical properties of the cartilage in response to load fluctuate with respect to time such that prolonged loading exposure causes greater deformation (41). Research by Gruber et al. (42) in runners determined that the frequency content of impact parameters may significantly contribute to injury risk as the capacity of the various tissues and mechanisms to transmit and attenuate force is frequency dependent (i.e. tissue could become overloaded pushing the knee outside its envelope of function) (42).



## **Load monitoring in athletes**

Due to proposed links between load and injury, as well as load and performance, load monitoring in athletes is currently a hot topic in the area of sports (18, 43). Arguably, most elite level coaches are well versed in developing their athletes and the requirements that must be met in order to achieve optimal sports performance outcomes. Through athlete monitoring, coaches are empowered with methods of monitoring the progress of these outcomes. This is achieved through methods that enable them to: evaluate athletic potential; establish the current status of their athletes; quantify the impact of the training on their athletes (i.e. dose-response); a means of measuring progress; and to be able to effectively observe athletes in their standard environments. Monitoring is inclusive of both injury and performance outcomes, and a variety of methods have been introduced across a multitude of sports targeted at measuring these outcomes.

Within the load monitoring spectrum are two specific areas of focus: internal loads and external loads (19). Internal loads refer to the physiological loads placed on athletes as a result of training and sports participation, injuries, and illness, psychological stress, and fatigue (19). External loads refer to the mechanical loads impacting the body including things such as distance, speed, impact loads, and forces generated by the body that place loads on the different tissues (44, 45). In a non-clinical setting (e.g. a pitch or court), the majority of these variables are assessed based on surrogate measures. An example of this is the session rating of perceived exertion (session-RPE) method which functions as a metric for internal training load as it is strongly associated with blood lactate measures (46). Measures of internal training load are used to quantify physiological variables (47). These metrics can include blood lactate, testosterone, cortisol, heart rate (resting, max heart rate, heart rate variability), creatine kinase levels, and session-RPE. Across the basketball literature, a number of studies have evaluated several of these physiological variables. Relationships have been reported between things such as heart rate, blood lactate, markers of inflammation and oxidative stress relative to power, strength, speed, agility, anaerobic performance, and muscle soreness (48); session-RPE and summated heart rate zone score (46); session-RPE and heart rate (49); and session-RPE and salivary cortisol in games (50).

The relationship between session-RPE and injury has yet to be reported in the basketball literature. Recent research in other sports has produced evidence supporting the importance of quantifying and monitoring internal and external loads with respect

to injury prevention, rehabilitation and management, illness, wellbeing, physical performance, and team success (18, 43). Given the nature of a basketball season, efficient and effective methods of load/injury monitoring are needed. This would allow staff to make quick, informed decisions and modifications to training and treatment in order to keep athletes performing optimally and injury free in order to promote better chances of success in their sport.

As lower limb injuries are the most common in basketball, monitoring lower limb loads specifically is important. To accomplish this task, several methods have been identified in the literature. Three-dimensional (3D) motion capture systems use a combination of force plates, cameras, and electro-goniometers to measure kinetics and kinematics during human motion (51). However, despite their accuracy and effectiveness, the use of these systems is limited in terms of both cost and being confined to a laboratory setting. Over the last decade, the development of inertial sensors to measure human movements using accelerometers, gyroscopes, and magnetometers has seen less reliance on 3D motion capture. These inertial sensors are more economical, small, and usable outside of laboratory settings. Additionally, they have been found to be reliable and valid in measuring variables including gait phases and whole body and segmental accelerations (52). Previously, research on the validity and reliability of accelerometry for assessing impact loads in jumping tasks has reported a strong correlation between peak resultant acceleration and ground reaction force in hopping and jumping tasks (53). Additionally data obtained from accelerometers were able to indicate mechanical loading reliably in track and field athletes (54). Though it is a known limitation that accelerations measured via sensors on the skin can potentially overestimate the magnitude of these impact accelerations (55), it provides an easy and reliable means of measuring and monitoring impact loading (56). Using inertial sensors (e.g. wearable accelerometers) in trainings or in-game (57) to monitor tibial acceleration may allow for a better understanding of the typical load experienced by the lower limb tissues during an actual basketball game.

Currently, the literature notes that excessive impacts and loading rates predispose individuals to injury (55, 58, 59). When considering that cumulative loading is a product of the impulse (loading rate) taken from the knee moment during stance/impact and the frequency of these stance/impacts, tibial acceleration may also serve as a surrogate measure for load providing an indication of the type of repetitive loading that the knee experiences during a basketball training/game (40). This may

allow for a better idea of what an athlete's cumulative knee loading exposure may be and provide insight into prevention of knee injuries which are common in basketball (40, 60). Thus, developing inertial sensor use in monitoring and predicting lower limb loads with respect to basketball training loads, performance and injury could provide a valuable tool for both coaches and clinicians to use in the sport.

### **Injury surveillance**

There are a number of injury definitions used in basketball injury surveillance (12-14). Time-loss is a common injury definition used for injury surveillance in team sports (61, 62). Though this definition makes identification of the injuries simple, it likely captures the fewest number of injuries. Another issue with this method is that it does not reflect the true magnitude of the injuries (26, 63). It is common for many athletes to continue to train and compete even when injured by relying on various means such as medications and bracing, modifying training or reducing the total training volume or intensity in order to be able to complete the season (63). This is considered a particular issue in basketball where there are a high number of overuse injuries, in which there is no one specific incident to pinpoint the onset of injury and pain (8). It is possible that a starter may play through an overuse injury if it is at a critical point in the season for the team. Surveys taken of athletes across multiple different sports allude to the notion that this is common practice for athletes to train and compete while experiencing pain and functional limitations from an injury (64, 65). Thus, as a result of the standard time-loss definition of injury used in many studies, the magnitude and severity of the overuse injury problem in sports such as basketball is poorly understood (66, 67).

Therefore, in order to determine the training load-injury relationship in basketball, the first step required is to more accurately describe the magnitude of the injury problem. Recently, the Oslo Sports Trauma Research Centre (OSTRC) published an overuse injury questionnaire (68), which has been found to be an effective method for registering overuse injuries across a number of sports including tennis, cycling, floorball, handball, volleyball, and cross country skiing (63, 69). The self-reported questionnaire is completed once weekly by each athlete over the course of their season. It is an attractive tool for practitioners as it is a simple, cost effective approach to athlete monitoring, which is key to practical implementation (63, 69). Therefore, the use of this questionnaire may be the most simple, reliable, and valid means of examining the training load-injury relationship.

## **Purpose of the Thesis**

The overall aim of this thesis was to quantify training load in basketball and investigate the relationship between training load and injuries (specifically, non-contact, musculoskeletal lower limb injuries) in male professional basketball players.

The specific objectives of this thesis were to:

1. Review the evidence for the biomechanical factors associated with increased risk of knee injuries (the most common lower limb injury in basketball).
2. Review how cumulative lower limb loading may be a more important metric to monitor with respect to lower limb injury risk.
3. Determine the magnitude of the overuse injury problem in a professional basketball team.
4. Quantify the bilateral lower limb loads (in terms of counts and intensities of impacts) experienced by the athletes during basketball trainings using wearable accelerometers.
5. Describe bilateral lower limb loads experienced by athletes during basketball trainings with wearable accelerometers using an applied musculoskeletal tissue adaptation metric.
6. Quantify session-RPE over a professional basketball season.
7. Investigate the relationship between session-RPE and injuries over a professional basketball season.
8. Investigate how different load monitoring strategies may be associated with knee injury in a professional basketball player using a case study.

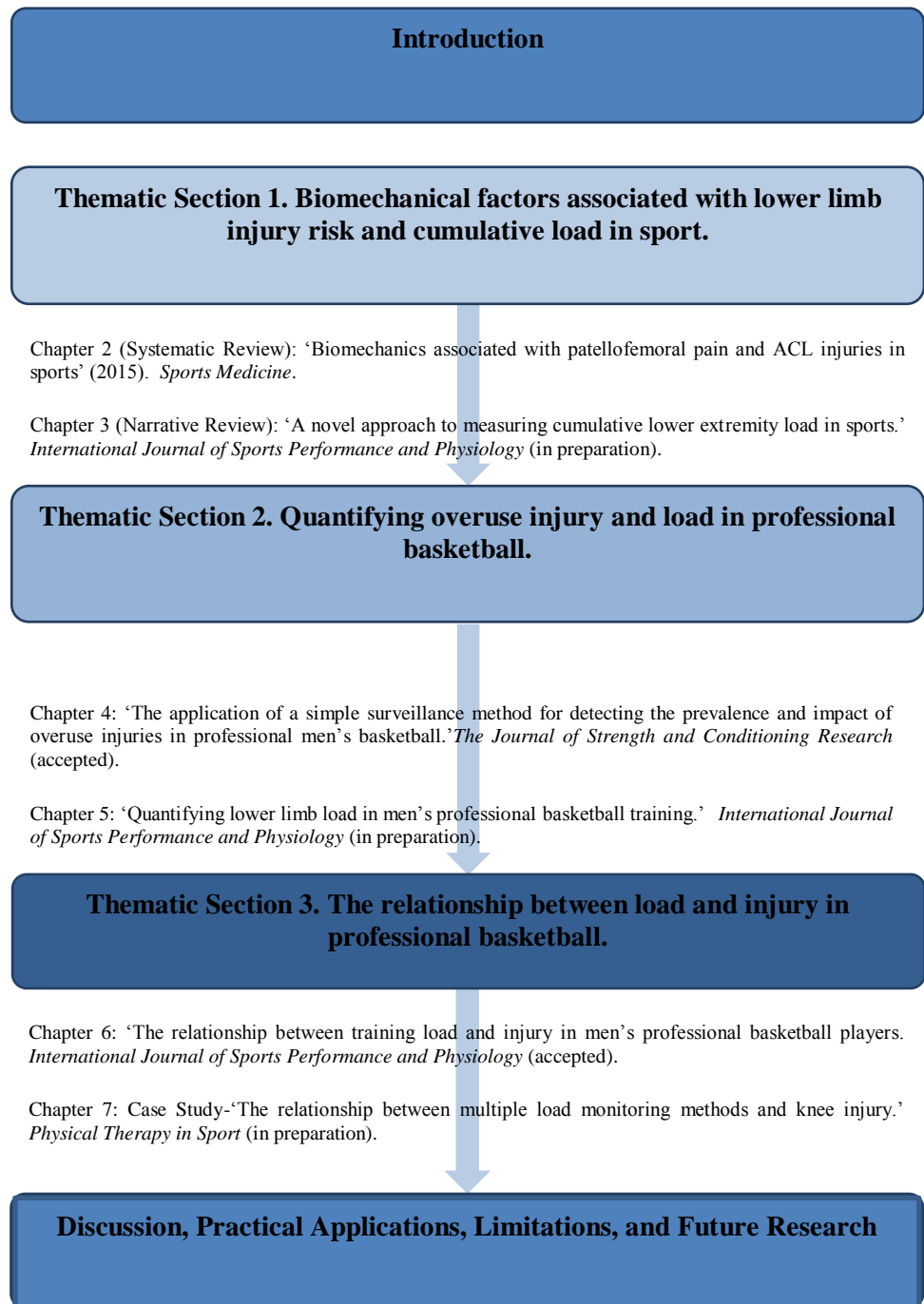
## **Significance of the Research**

The quantification of the training load-injury relationship requires the implementation of an athlete monitoring system. In order to set up an effective athlete monitoring system in professional basketball, the efficacy of the methodologies and metrics must first be established. Despite the tremendous growth in sports science, the specific methods and measures most relevant and informative for monitoring athletes in professional basketball have yet to be identified. By determining which methods and measures are most appropriate with respect to injuries, training loads, and performance, monitoring systems can be developed which may be beneficial for athletes, coaches, and support staff in the management of athletes as well as the team (e.g. programming,

injury management, training, and recovery strategies). By establishing best practices for the quantification of load in professional basketball, teams may be able to keep players relatively free from non-contact, preventable injuries while simultaneously enhancing athlete resilience through training load-stimuli that best prepare them for the most demanding physical requirements presented during competition. Further, by having multiple, effective methods for quantifying loads, teams can select the most appropriate metrics and methods for use with their athletes.

## **Structure of the Thesis**

This thesis is comprised of three, sequential sections (See Figure 1. Thesis flow chart). The first thematic section (Chapters 2 and 3) includes: a systematic review of the research specific to biomechanics associated with increased risk of knee injuries in sports (Chapter 2) and a narrative review of the importance and relevance of quantifying cumulative lower limb loading with respect to injury risk using an adapted tissue load equation (Chapter 3). The second thematic section (Chapters 4 and 5) quantifies overuse injury by evaluating the magnitude and prevalence of commonly identified overuse injuries (ankle, knee, low back) in professional basketball over a single season using a self-reporting overuse questionnaire (Chapter 4); quantifies the bilateral lower limb loads (in terms of counts and intensities of impacts) experienced by the athletes during basketball trainings using wearable accelerometers; and investigates the use of wearable accelerometers to quantify bilateral lower limb loads in professional basketball using an adapted tissue load metric (Chapter 5). The focus of the final section is the relationship between load and injury in professional basketball, including using the session-RPE method. Chapter 6 explores the relationship between training load and overuse injuries across a single season of men's professional basketball; and, lastly, a case study exploring the relationship between three separate load monitoring methods and knee injury in a male professional basketball player (Chapter 7).



**Figure 1. Overview of the thesis (Thesis Flow Chart)**

## CHAPTER 2: BIOMECHANICS ASSOCIATED WITH PATELLOFEMORAL PAIN AND ACL INJURIES IN SPORTS: A SYSTEMATIC REVIEW

This chapter comprises the following paper published in Sports Medicine:

Weiss, K., & Whatman, C. (2015). Biomechanics associated with patellofemoral pain and ACL injuries in sports. *Sports Medicine*, 45(9), 1325-1337.

### Abstract

*Background:* Knee injuries are prevalent among a variety of competitive sports and can impact an athlete's ability to continue to participate in their sport, or in the worst case, end an athlete's career.

*Objective:* To evaluate biomechanics associated with both PFPS and ACL injuries (in sports involving landing, change in direction, or rapid deceleration) across the three time points frequently reported in the literature: pre-injury, at the time of injury, and following injury.

*Methods:* A search of the literature was conducted for research evaluating biomechanics associated with ACL injury and PFPS. The Web of Science, SPORTDiscus, EBSCO, PubMed, and CINAHL databases to March 2015 were searched and journal articles focused on ACL injuries and PFPS in sports that met the inclusion criteria were reviewed. The search methodology was created with the intent of extracting case-controlled, case, and cohort studies of knee injury in athletic populations. The search strategy was restricted to only full text articles published in English. These articles were included in the review if they met all of the required selection criteria. The following inclusion criteria were used: (1) The study must report lower extremity biomechanics in one of the following settings; (i) a comparison of currently injured and uninjured participants, (ii) a prospective study evaluating risk factors for injury, or (iii) a study reporting on the injury event itself. (2) The study must include only currently active participants who were similar at baseline (i.e. healthy, high school level basketball players currently in-season) and include biomechanical analysis of either landing, change in direction, or rapid deceleration. (3) The study must include currently injured participants. The studies were graded based on quality, which served as an indication of risk of bias. An adapted version of the STROBE guidelines were used to rate observational research.

*Results:* Fifteen journal articles focusing on ACL injuries and PFPS in sports met the inclusion criteria. These included three associated with both ACL injuries and PFPS across multiple time points. There was limited evidence for an association between ankle biomechanics and knee injury, with only one ACL injury study identifying decreased plantar flexion in association with injury.

*Limitations:* Only prospective studies can determine biomechanical risk factors associated with ACL injuries and PFPS. Case-studies and case-control studies do not allow for the determination of risk factors associated with both ACL injuries and PFPS as there is no certainty regarding the presence of the observed biomechanics prior to the onset of injury. Further, each study design has its own set of limitations. Lastly, the majority of the studies included in this review had adult female participants.

*Conclusion:* By evaluating several different study designs looking at knee injuries during high risk manoeuvres, we were able to obtain a holistic perspective of biomechanics associated with PFPS and ACL injuries. Looking at different biomechanical research approaches allowed us to assess not only the mechanism of injury, but also to look for commonalities in biomechanics (in particular, altered frontal plane mechanics at the knee and altered sagittal plane mechanics at the knee and hip) between injured and uninjured participants pre-injury, at the time of injury, and following injury, to better understand potential causes of PFPS and ACL injury. Development of injury prevention programs should focus on correcting these mechanics observed across the three time points during high risk manoeuvres as this may help decrease the prevalence of ACL injury and PFPS. Programs focusing not only on neuromuscular training, but also skill specific training focused on correcting mechanics during these high risk manoeuvres may be of greatest benefit regarding prevention. Future research should consider the impact of cumulative loading on knee injury risk. Additionally, better techniques for assessing mechanics in-game are needed in order to facilitate injury prevention and screening strategies.

*Key Points:*

- . Both ACL injuries and PFPS are associated with similar biomechanics
- . Biomechanics associated with the hip and knee at all time points (pre, at and following injury) occurred predominantly in the sagittal (flexion/extension) and frontal (abduction/adduction) planes.



## Introduction

Knee injuries are prevalent among a variety of competitive sports, especially those that involve stop-start movements, changes in direction, jumping and landing both with and without passing and/or shooting a ball (70). Two of the most common sports related knee injuries are PFPS and ACL injuries. In athletic populations, as many as 25% of all knee problems resulting from participation in sport are attributed to PFPS (71). PFPS is a condition in which pain is localized over the anterior aspect of the knee and aggravated by movements that increase compressive forces acting on the patellofemoral joint such as landing from a jump, squatting, and running. PFPS can be debilitating, leading to diminished ability to perform work and sports related tasks without pain. ACL injuries are the most costly with respect to cost of care and cost per hour of participation in sport (25). Previous studies noted that 70 to 84% of all ACL injuries are non-contact in nature (33, 72). The majority of ACL injuries occur during changes in direction, rapid deceleration while running, cutting manoeuvres combined with deceleration, landing after a jump, and pivoting on a planted foot (73, 74).

In general, injuries to the knee are more severe in nature and more costly in comparison to other injury sites (75, 76). More specifically, PFPS and ACL injuries are of particular concern as they often result in long and expensive rehabilitation (25, 77-79). In some cases, these particular injuries decrease the athlete's ability to continue to participate in their sport, or in the worst case, end the athlete's career. They can impact players throughout their lives by increasing their risk of degenerative musculoskeletal conditions such as osteoarthritis, and potentially reducing their quality of life (80-82).

While there is considerable research focused on knee injury rehabilitation, there is a need for better prevention strategies if we hope to mitigate some of the negative effects of the injuries themselves. Finch (83) developed a model for injury prevention adapted from the four step model created by van Mechelen (84). This sports injury research framework, Translating Research into Injury Prevention Practice (TRIPP), is comprised of six stages: 1) injury surveillance; 2) establishing the aetiology and mechanisms of injury; 3) development of preventative measures; 4) "ideal conditions"/scientific evaluation; 5) intervention context to inform implementation strategies; and 6) an evaluation of the effectiveness of preventive

measures in an implementation context. This review focuses on the second stage of this model.

Previous reviews have evaluated knee injury risk with respect to the athlete's playing environment (78), anatomy (38, 85), sex (78, 86), and biomechanics (38, 78, 85, 86). As anatomy and sex cannot be modified, it is important to identify modifiable factors such as biomechanics associated with ACL injury and PFPS, in order to develop and improve prevention strategies. In particular, biomechanics can be effectively used in the second step of the TRIPP framework as a means of illustrating and measuring both the risk factors and mechanisms of knee injuries (83). There is a lack of understanding surrounding the relationship between biomechanics associated with PFPS and ACL injuries. Further, many studies have focused solely on healthy populations, whereas others have focused on populations that are already injured (87-89). When these populations are presented separately, it gives an incomplete picture of the biomechanics associated with these injuries. Hence, there is a need to evaluate studies examining biomechanics across a variety of conditions including at the time of injury, prospectively, and between injured and uninjured groups. This will allow an evaluation of common biomechanics present prior to, during, and following injury. By evaluating biomechanics across these three time points, we can gain a clearer understanding of the risk factors and associated biomechanics related to the time of injury and following injury for PFPS and ACL injuries and can use this information to guide screening and prevention strategies. This may benefit prevention programs utilised by athletic groups including non-injured and previously injured athletes. Research in ACL injury prevention programs has determined neuromuscular training to be most effective (90, 91). The group that benefitted most from this type of training were female athletes under the age of 18. Currently, there is a lack of research focused on prevention programs designed to mitigate biomechanics associated with both ACL injuries and PFPS. Prevention programs targeted at biomechanics associated with both PFPS and ACL injuries will have a broader impact regarding knee injury prevention.

It is important to note, however, that only prospective studies can identify true risk factors for these injuries, as case studies and case-control studies cannot substantiate the presence of the observed biomechanics prior to the inciting injury.

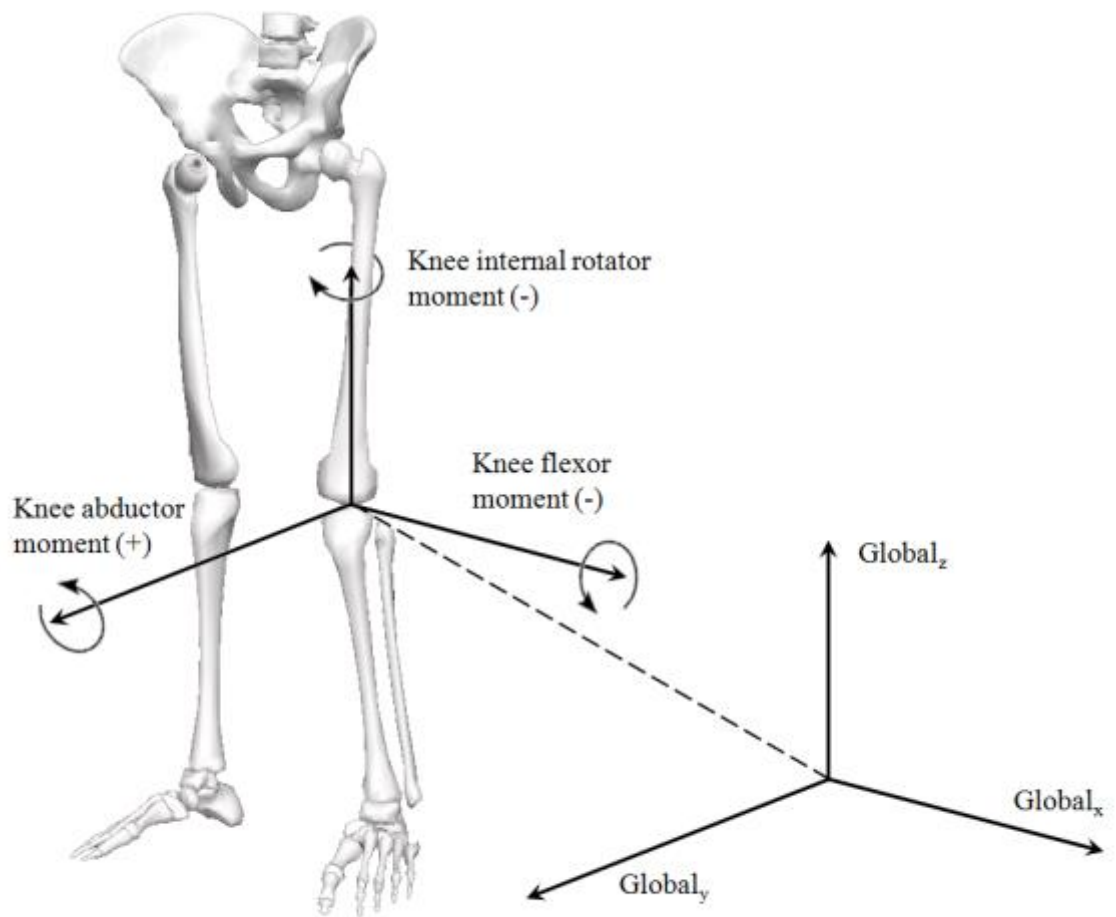
Therefore, the purpose of this systematic review was to summarise the common

biomechanics associated with two highly prevalent knee injuries (PFPS and ACL injuries) in sports (involving landing, change in direction, or rapid deceleration) across the three time points commonly reported in the literature: pre-injury, at the time of injury, and following injury.

## **Methods**

### **Definition of Terms**

A number of papers examining biomechanics associated with ACL injury and PFPS use different terminology in their description of biomechanical variables included in their methods and analysis. Thus, for the context of this review, joint forces (i.e. moments) will refer to those externally applied to the joint at the distal end of the segment (see Fig.2). Therefore, in the sagittal plane, an extensor moment acting on the knee joint would extend the knee, whereas a flexor moment would act to flex the knee. In the frontal plane, an adduction moment acting on the knee would adduct the knee in a varus position meaning the distal end of the tibia is moving towards the midline of the body, resulting in a knees out or bowlegged position, and an abduction moment would result in the distal tibia moving away from the midline of the body leading to a knees in or knock-kneed position. Lastly, in the transverse plane, an external rotation moment rotates the knees externally, and an internal rotation moment rotates the knees internally (92).



**Figure 2. External knee moments with three degrees of freedom (flexor (-x)/extensor (+x), abduction (+y)/adduction (-y), and internal (-z)/external rotation (+z)) defined locally and with respect to the global coordinate system [51].**

### **Literature Search Methodology**

The methods used for this systematic review follow the structure outlined in the guidelines given by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (93). We considered the strength of the study design (using an adapted version of the STROBE guidelines (94)) and its ability to accurately assess biomechanical variables. The STROBE (Strengthening the reporting of observational studies in epidemiology) Statement is a checklist consisting of 22 items that are regarded as critical for reliable reporting of observational studies.

### **Search Parameters and Eligibility Criteria**

A search of the literature was conducted for knee risk factors and mechanisms. The Web of Science, SPORTDiscus, EBSCO, PubMed, and CINAHL databases to March 2014 were searched for terms linked with the Boolean operators ('AND', 'OR',

‘NOT’): ‘knee\*’, ‘patellofemoral’, ‘ACL’, ‘injur\*’, ‘biomech\*’, ‘athlete\*’, ‘cohort’, ‘case-control’, ‘sidestepping’, ‘cutting’, ‘change in direction’, ‘landing’, or ‘deceleration’. The search methodology was created with the intent of extracting case-controlled, case, and cohort studies of knee injury in athletic populations.

The search strategy was restricted to only full text articles published in English. One investigator (KW) reviewed all the titles generated by the database searches, and extracted only appropriate abstracts. Those abstracts that were deemed as suitable guided the retrieval of the full texts. These articles were included in the review if they met all of the required selection criteria.

We did not blind the study author or the study’s findings. The following inclusion criteria were used:

- (1) The study must report lower extremity biomechanics in one of the following settings; (i) a comparison of currently injured and uninjured participants, (ii) a prospective study evaluating risk factors for injury, or (iii) a study reporting on the injury event itself.
- (2) The study must include only currently active Participants with similar baseline measures and include biomechanical analysis of either landing, change in direction, or rapid deceleration.
- (3) The study must include currently injured participants.

### **Assessment of Study Quality**

Two authors graded the studies based on quality, which served as an indication of risk of bias. We used an adapted version of the STROBE (94) guidelines which is used to rate observational research. The studies included in this review were all rated on 10 specific items on a zero to two point scale (see Table 1. Methodological quality assessment). The study was considered to have a low risk of bias if it was rated as high quality (score of  $\geq 14/20$ ) or a high risk of bias if it scored  $\leq 13/20$  (95). The score specifications for high- and low-quality studies were determined by agreement between the authors. Any disagreement in ratings between authors was resolved by a consensus. Once an agreement was reached for all the ratings of the studies, overall quality scores were determined by calculating the sum of each of the criteria, leading to a total score out of 20. The scoring criterion used is presented in Table 1.

## **Data Extraction**

For studies that met the quality criteria, data were extracted, including study name, sport type, aim/focus, study design, participants' characteristics, methodological quality, key variables, and outcome measures (Table 2 shows summary information for each of the studies and table 3 shows a summary of common biomechanics associated with ACL injury and PFPS at the ankle, knee, and hip across each time point).

**Table 1. Methodological quality assessment**

	Criteria	Boden et al. (73)	Boling et al. (37)	Cochrane et al. (96)	Ebstrup and Bojsen-Moller (97)	Hewett et al. [5]	Hewett et al.[6]	Kobayashi et al. [7]	Koga et al. [8]
1	Power analysis was performed and/or justification of study sample was given.	0	0	0	0	0	0	0	0
2	Describes relevant dates (period of recruitment &/or, exposure, follow-up, data collection).	2	1	2	2	2	2	2	2
3	Athlete characteristics (sport, experience, activity level or level of play at time of test) and demographics (sex, age, body height/mass, and injury status) were clearly defined.	2	2	1	1	2	1	1	2
4	Inclusion and exclusion criteria were given.	2	2	1	0	2	1	2	0
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	0	0	2	0	0	0
6	Describes methods of follow-up, analysis of injuries, and data collection procedures. Methods included enough detail to allow replication of the testing. Testing devices, number of trials, number and duration of test, data analysis process, and injury evaluation were included when applicable.	2	2	2	0	2	2	2	2

<b>7</b>	Test-retest reliability of measurement devices or analyses were reported.	2	1	1	0	2	1	0	0
<b>8</b>	Indicated number of participants with missing data and explains how it was addressed.	2	0	0	0	0	0	1	1
<b>9</b>	Outcome variables were clearly defined.	2	2	2	0	2	2	2	2
<b>10</b>	Statistical analyses were appropriate.	2	2	2	0	2	2	1	2
<b>Total Score</b>	(Maximum=20 points)  0=clearly no; 1=maybe or inadequate information; 2=clearly yes	<b>12</b>	<b>14</b>	<b>11</b>	<b>3</b>	<b>16</b>	<b>11</b>	<b>11</b>	<b>11</b>



## **Results**

### **Search Results**

The initial search protocol produced a total of 8,542 records from 5 electronic databases, with an additional 29 records being from other sources (i.e. references from other papers). Figure 3 shows the flow of information through the systematic review (PRISMA Flow Chart). The removal of 4,257 duplicates left a total of 4,314 publications for the article selection process. The title-based selection eliminated 3,994 publications, and the abstract selection process that followed eliminated an additional 260 publications. The final 60 publications were then reviewed using the outlined inclusion/exclusion criteria, resulting in another 45 papers being excluded, leaving a total of 15 studies as part of this systematic review. Inclusion of each article was the result of a group consensus. Figure 3 gives details regarding the total number of studies evaluated for eligibility and inclusion in our review along with the reasons articles were excluded.

**Table 2. Summary of individual study characteristics.**

Study	Design	Participants <sup>a</sup>	Sports	Methods
Wilson and Davis (98)	Case-control	20 females with PFPS & 20 healthy female controls (23.7(3.6);23.3(3.1))	Physically active participants	Peak isometric lateral trunk flexion, hip abduction, hip external rotation, knee flexion, knee extension strength, hip and knee joint excursions and angular impulses during single-leg jumps.
Souza and Powers (99)	Case-control	21 females with PFPS & 20 healthy controls (27(6);26(5))	Physically active participants	Hip kinematics and activity level of hip musculature during running, drop jumping, and step-down manoeuvres.
Wilson et al. (100)	Case-control	21 females with PFPS & 20 healthy controls (23.7(3.6);23.3(3.1))	Recreationally active participants	Participants performed a functional lower extremity exertion protocol including repetitive single-legged jumps. Pain, exertion, hip and trunk strength, and 3D lower extremity joint mechanics were recorded pre-and post-exertion protocol.
Noehren et al. (31)	Cohort	400 healthy female runners, 15 developed PFPS (aged 18-45, running a minimum of 20 miles/week)	Running	400 female runners performed a gait analysis and were tracked over 2 years for injuries. 15 developed PFPS and their initial running mechanics were compared to an equal number of uninjured runners
Boling et al. (37)	Cohort	1597 midshipmen (606 females and 991 males)	Naval academy	Participants were prospectively followed for a maximum of 2.5 years. Each participant performed baseline data testing pre-freshman year at the Naval academy. 3D motion analysis during jump landing, 6 lower extremity isometric strength tests, and a postural alignment measurements were taken.

Myer et al. (101)	Cohort	Middle and high school female athletes (n=240). 131 controls (13.4(1.6)) and 14 new PFPS (12.7 (1.0))	Middle and high school basketball players	Athletes were evaluated by a physician for PFPS and for landing biomechanics prior to their basketball season, and then they were monitored for PFPS injury during their competitive seasons.
Hewett et al. (102)	Cohort	205 female athletes. 9 athletes had a confirmed ACL rupture. Injured participants (15.8 (1.0)) and controls (16.1(1.7)).	Soccer, basketball, & volleyball	Athletes were prospectively measured for neuromuscular control using 3D kinematics and joint loads (angles and moments) during a jump landing manoeuvre.
Verrelst et al. (103)	Cohort	69 female participants (19.24(0.86)). 21 developed the injury.	Students in a physical education program	Participants completed a single-legged drop jump and kinetics and kinematics were collected. Participants were followed prospectively and those who developed PFPS were compared to uninjured participants
Hewett et al. (104)	Case	10 female and 7 male ACL-injured players	Professional American basketball players.	Analyses of still captures from 23 coronal or 28 sagittal plane videos performing similar landing and cutting tasks. Lateral trunk angle and knee abduction angle during ACL rupture were assessed.
Kobayashi et al. (105)	Case	1,718 participants (838 males and 880 females). Male (22.6(7.0)); female (20.5(7.4))	Male sports: soccer, ski, basketball, rugby, handball, baseball, judo, American football, volleyball, sumo, other  Female sports: basketball, ski, handball, volleyball, track & field, judo, gymnastics, badminton, softball, tennis, other	The activity, injury mechanism, and dynamic knee alignment at time of ACL injury were assessed.

Boden et al. (73)	Case	29 videos of ACL participants (20 females, 9 males) were compared with 27 (15 females, 12 males) videos of controls performing similar manoeuvres	Professional basketball	Joint angles were analysed in 5 sequential frames in the frontal or sagittal planes, starting at initial ground contact. Hip, knee, and ankle ankles were measured in both planes. Videos of controls and injured performing similar manoeuvres were compared.
Koga et al. (106)	Case	10 ACL injury videos from female handball and basketball matches	Handball and basketball	10 ACL injury videos were analysed using model-based image-matching to look at kinetics and kinematics.
Cochrane et al. (96)	Case	34 ACL injuries in men's Australian Football	Australian Football	34 ACL injury videos were analysed looking at manoeuvre, direction the knee 'gave way', running speed, knee angle, and cutting angle
Olsen et al. (107)	Case	20 ACL injuries (all females) in Norwegian handball	Norwegian team handball	20 videos were analysed during ACL injuries by three medical doctors and 3 national team coaches. Injury mechanism including kinematics as well as playing situations were observed.

**Table 3. Summary of associated biomechanics across each time point (pre-injury, time of injury, following-injury). ACL refers to anterior cruciate ligament injury; PFPS refers to patellofemoral pain syndrome; ↑ refers to increased; ↓ refers to decreased**

Study	Study design	Injury	Biomechanics		
			Hip	Knee	Ankle
Pre-injury (cohort)					
Boling et al. (37)		PFPS	↑ Internal rotation angle	↓ Flexion angle/extension strength/flexor moment	
Myer et al. (101)		PFPS		↑ Abduction moment/abduction load	
Hewett et al. (102)		ACL		↑ Abduction angle/abduction moment	
Verrelst et al. (103)		PFPS	↑ Transverse plane motion		
Time of injury (case)					
Hewett et al.(104)		ACL		↑ Abduction angle	
Kobayashi et al. (105)		ACL		Dynamic valgus	
Boden et al. (73)		ACL	↑ Flexion	↑ Abduction	↓ Plantar-flexion
Ebstrup and Bojsen-Moller (97)		ACL		Varus coupled w/femoral external rotation; valgus coupled w/femoral internal rotation	
Koga et al. (106)		ACL		Valgus coupled w/tibial internal rotation	

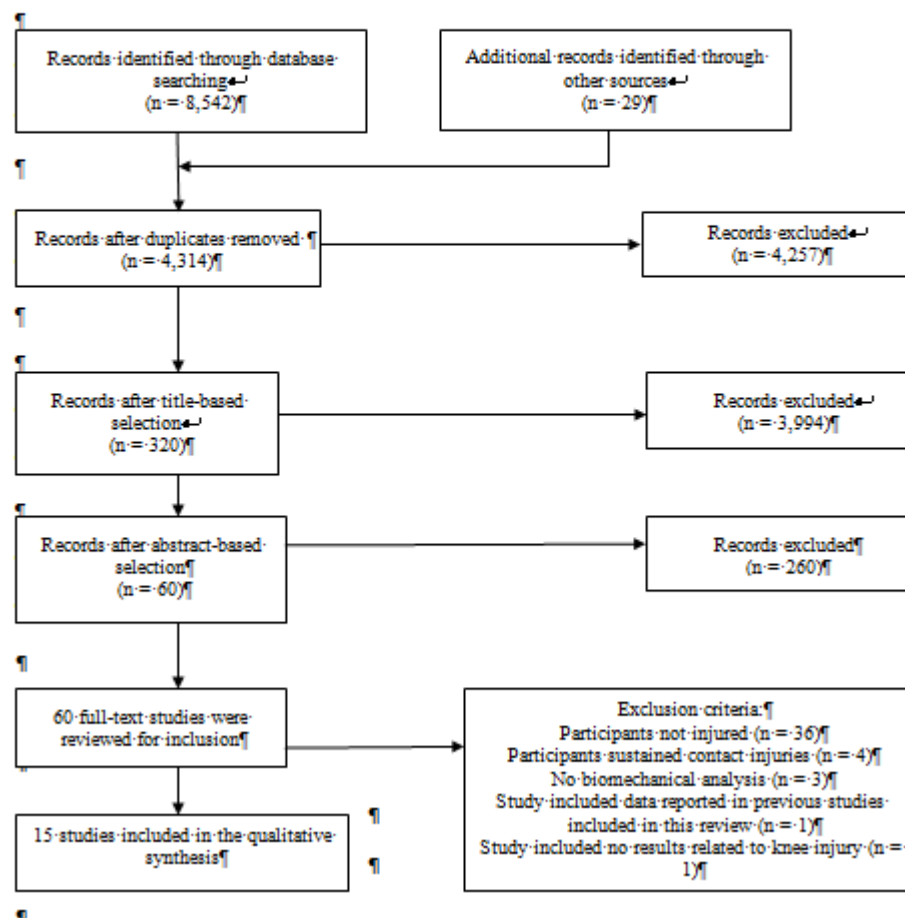
Cochrane et al. (96)	ACL	>30° Flexion/valgus/internal rotation		
Olsen et al. (107)	ACL	Valgus coupled w/external rotation and shallow flexion angles		
Following-injury (case-control)				
Wilson and Davis (98)	PFPS	↓ Abduction/external excursion/adduction impulses	rotation;↑	adduction
Souza and Powers (99)	PFPS	↑ Peak internal rotation		
Wilson et al. (100)	PFPS	↑ Adduction angle/flexion angle/adduction angular impulse; ↓ internal rotation angle		

## **Study Characteristics**

There were a total of fifteen studies including three case-control laboratory, five prospective cohort, and seven case studies that were included in the systematic review. Seven studies focused on PFPS and eight studies looked at ACL injuries. There was a large range in sample size, participant age, sports, and skill levels of the participants across the studies. Eleven of the studies consisted entirely of female participants, one study consisted only of male participants, and three studies included mixed samples. Ten studies included adults only, three studies evaluated both adults and adolescents together, and two studies included adolescents only. The nature of the injury diagnosis differed between studies. Eleven of the studies used the diagnosis of a medical professional, three studies used licensed physical therapists, and one study did not specify. Nine of the papers (60%) included a sample size of 0-49 participants, two (13%) had 50-99 participants, two (13%) had 200-249 participants, one (7%) had 1550-1599 participants, and one (7%) had 1700-1749 participants. Eight of the papers included recreationally active participants, six included elite level athletes, one paper evaluated both recreational and elite level athletes, and a total of 18 sports were analysed across all 15 included studies (See Table 2 for additional information regarding each study).

## **Study Quality**

The case-control studies had an average study quality score of 15/20; the prospective cohort studies had an average score of 16/20; and the case studies had an average score of 10/20. The scoring criteria used are shown in Table 1.



**Figure 3. PRISMA flow diagram of article selection with inclusion/exclusion criteria.**

### Results of Individual Studies

Evidence across several studies evaluating hip mechanics observed the following biomechanical variables as being associated with PFPS: increased adduction angle (3 studies (31, 98, 100); quality score range 16 to 17); increased adduction impulse (e.g. force acting for a given time) (2 studies (98, 100); quality score 16); increased internal rotation angle (3 studies (37, 99, 103); quality score range 13 to 16), with 1 study (100) (quality score 16) finding conflicting evidence of decreased internal rotation angle as a risk factor; and increased flexion angle (1 study [22]; quality score 16).

Studies evaluating hip mechanics associated with ACL injury found increased hip flexion to be a risk factor associated with injury (2 studies (32, 73, 100); quality



score range 12 to 16).

There was evidence from 2 studies regarding knee mechanics and associated PFPS risk: decreased flexion angles (1 study (37); quality score 14); decreased flexor moment (1 study (37); quality score 14); and increased abduction loads (1 study (101); quality score 16).

Observations from studies looking at knee mechanics associated with ACL injury found: decreased flexion angles (2 studies [28, 29]; quality score range 11 to 14); increased abduction angle (7 studies (73, 96, 97, 102, 104, 105, 107); quality score range 11 to 16); increased abduction moment (1 study (97, 101, 102, 104, 108); quality score 16); increased internal rotation angle (3 studies (73, 97, 106); quality score range 3 to 11); and conflicting evidence reporting increased external rotation angle (2 studies (97, 107); quality score range 3 to 13), and increased adduction angle (1 study (97); quality score 3).

There was limited evidence for an association between ankle biomechanics and knee injury, with only one study (73) (quality score of 12) identifying decreased plantar flexion as a risk factor for ACL injury.

Table 3 shows the key biomechanics associated with ACL injury and PFPS at the ankle, knee, and hip across each time point.

## **Discussion**

### **Summary of Evidence**

This review summarised the literature investigating biomechanical variables associated with knee injuries, namely ACL injury and PFPS in sports (involving landing, change in direction, or rapid deceleration) across three time points. Fifteen studies including three case-control laboratory, five prospective cohort, and seven case studies evaluated a variety of biomechanical variables at the hip, knee, and ankle with respect to knee injury. It is important to note that the variables included in this review were evaluated across several study designs to include participants pre-knee injury, at the time of injury, and currently injured participants. This allowed us to accumulate evidence of biomechanical variables that are present in all three instances in order to better understand how these various biomechanics relate to PFPS and ACL injuries. Based on our review, the association between knee and hip biomechanical variables

and PFPS and ACL injuries is supported by the best evidence from multiple studies. There is limited evidence for ankle biomechanics being associated with these injuries.

With respect to the knee, the most common biomechanical variables associated with both ACL injury and PFPS across studies were: increased abduction loading and shallow knee flexion angles. During dynamic knee abduction, the medial collateral ligament, medial patellofemoral ligament, and ACL are strained as a result of trying to prevent this excessive abduction movement (109, 110). When a knee abduction moment is present, tensile strain is increased on the medial collateral ligament and the ACL (111). Several of the prospective studies observed greater abduction loading in the injured group. It is possible that repetitive increased abduction loading, rather than a single large abduction load, led to injury. Cumulative, chronic abnormal frontal plane loading may be the inciting factor that led to injury (24, 28). This abduction moment is often attributed to excessive hip adduction and internal rotation, often caused by weak hip musculature (112, 113). Generally, increased knee abduction indicates a decrease in the ability of the hip musculature to absorb energy/force during the deceleration portion of landing tasks. This increases impact forces on the knee which in conjunction with lower extremity postures that increase strain on the patellofemoral joint and the ACL, create a situation that significantly increases the risk of injury to the knee (114). When engaged in weight bearing activities such as landing and sidestepping, increased knee abduction moments can place greater tensile stress on the ACL, resulting in injury (92). Increased abduction moments can lead to disruption of normal sagittal plane tibiofemoral mechanics, increasing anterior tibial translation and may prevent normal knee joint mechanics which can contribute both to PFPS and ACL injury risk (101, 102, 108).

In addition to knee frontal plane mechanics, knee sagittal plane mechanics, and more specifically, knee flexion angle, also appeared across a number of studies as biomechanics associated with ACL injury and PFPS. When loading of the knee joint occurs primarily in the frontal plane during dynamic sports-related tasks, mechanics may be altered in the sagittal plane, which decreases stability of the joint and loads the ACL (115). When examining knee flexion angles, Nagano et al. (88), determined that knee flexion angles less than 30 degrees resulted in a large strain force on the ACL caused by quadriceps contraction, especially during unilateral landing as a means to prevent falling (88, 109, 110). Loading of the quadriceps can lead to anterior tibial displacement, knee internal rotation, and knee abduction motions. In a predictive

laboratory-based study on ACL injury risk, the results indicated that small knee flexion during landing led to higher knee frontal plane loading and subsequent ACL injury risk (116). Decreased knee flexion angle has also been found to increase the risk of PFPS (99, 101). Shallow knee flexion angles accompanied by increased internal rotation may also increase the amount of patellofemoral contact force (99, 101). Co-contraction of the knee flexors may aid in preventing excessive quadriceps contraction, thereby enhancing knee joint stability and potentially decreasing large knee abduction moments during landing tasks (108). Regarding the ACL, a single study reported increased knee flexion angles in association with injury. During normal range of motion, the two bundles that comprise the ACL (the anteromedial and posterolateral bundles) are in a continuously rigid arrangement due to their adjacent sites of attachment. When the knee is in full flexion, the anteromedial bundle becomes rigid, and when the knee is in full extension, the posterolateral bundle becomes rigid, thus placing stress on the ACL at or near full flexion and full extension (117).

The most common hip biomechanic variable seen across both the ACL injury and PFPS studies reviewed was increased hip flexion. Given that the quadriceps flex the hip, it is possible that increased quadriceps activation as a result of decreased hamstring strength causes increased hip flexion while decreasing knee flexion, increasing the risk of ACL and PFPS. Following PFPS, increased hip flexion may be a compensatory mechanism by the body during various tasks to alleviate anterior knee pain by absorbing greater forces at the hip (via increased flexion) as opposed to the knee. Though only seen in the ACL injury studies, both increased hip adduction and internal rotation influence the knee joint centre, resulting in medial translation relative to the foot (102). When this happens, it contributes to dynamic knee valgus, which has been found to increase the risk of ACL injury and PFPS. As noted earlier this is often related to decreased hip muscular control (102). Increased hip abduction can also impact the knee as it leads to excessive movement of the body's centre of mass over the stance limb in sidestepping and single leg landings. This results in the ground reaction force acting on the lateral side of the knee, generating a large abductor moment at the joint, which places tensile strain on the medial soft tissue, especially the ACL and also the medial collateral ligament. The combined shift in the centre of mass over the centre of pressure of the stance limb, in conjunction with knee abduction (from excessive hip adduction and internal rotation) would have the largest potential to result in a knee abduction moment, which is associated with injury risk. When weakness of the hip

external rotators is present, this can cause increased internal rotation of the hip in conjunction with knee valgus (abduction), which increases lateral compressive forces acting on the patellofemoral joint (30, 118). Further, increased hip internal rotation may force the patella to align more laterally, which along with the shallow knee flexion angle, will potentially increase the patellofemoral contact stress resulting in PFPS (30, 119).

Decreased plantar flexion may be a risk factor for knee injury, possibly by decreasing the body's ability to attenuate force at the ankle joint (73). When ankle plantar flexion angle is small during dynamic sports tasks, the joint's ability to absorb the force acting on the body is decreased, requiring the body to compensate by using either a knee or hip load absorption strategy. This extra load on the knee joint places it at potentially increased risk of injury. This was only noted in a single ACL injury study.

Based on our findings, the evidence suggests that there are multiple biomechanical variables associated with both PFPS and ACL injury. The reduced ability of the lower extremity to dissipate forces during landing and sidestepping tasks appears to be an underlying intrinsic factor related to these injuries. The combination of increased frontal plane loading, particularly at the knee, in conjunction with decreased mechanical control of the hip, increases the stress acting on the tissues and structures of the knee. It appears that increased hip flexion present across PFPS and ACL injury studies contributes significantly to knee frontal plane loading (102). Thus, prevention programmes developed to mitigate this may be of benefit to decrease the prevalence of both these injuries. Beneficial training strategies include those focused primarily on neuromuscular training both pre-season and in-season. These methods have been found to be effective in decreasing knee injury risk factors in female athletes (120, 121). Future consideration of the impact of repetitive frontal plane knee loading may also be beneficial in knee injury prevention programming (24, 28).

To guide this review, we developed a rating system with the aim of establishing the quality of the included studies based on their methodology and research design. Assessing the quality of each study allows us to make more informed conclusions about each study's findings and their contribution to our understanding of biomechanics associated with ACL injury and PFPS. Based upon our rating system, we found prospective, cohort laboratory studies provide the best evidence in terms of

biomechanical risk factors as participants are all evaluated at a similar baseline and then compared following injury, allowing us to determine how biomechanical differences may have impacted overall risk. Secondary were the case-control studies, in which currently injured participants were compared to controls. However, because of this, these studies only evaluated PFPS. The weakness in this type of design is that it is difficult to determine whether the biomechanical differences are the result of the injury, or the actual cause of the injuries sustained by the participants. Lastly, the case studies using video analysis, though informative, are perhaps weakest in findings. Without having baseline comparisons with either the same participants performing the manoeuvres in game without injury as they did during the actual injury, it is difficult to determine whether the biomechanics performed during the injury were different from any other performance of the manoeuvre and whether they truly caused the injury to occur. Since PFPS is not an acute injury, only ACL injuries could be evaluated in this type of design. Therefore, the need for more prospective studies is highlighted as they appear to provide the strongest evidence regarding knee injury risk.

## **Limitations**

The limitations to this review relate to the different study designs as well as their participants. Case studies using video analysis have several limitations. It is primarily through visual inspection that the joint kinematic data are rendered, which may lead to a significant level of error with respect to estimating segmental position and joint angles. This method inhibits observation of continuous joint angle and position data, preventing analysis of angular velocity and acceleration data. Further, no kinetic data can be collected via video analysis. Prospective cohort studies performed in a laboratory setting have their own set of limitations. Though three-dimensional (3D) motion capture in a laboratory allows for kinetic and kinematic data to be collected, the tasks performed are meant to mimic movements during which injuries typically occur, and are not necessarily the actual injury mechanisms so direct comparisons between mechanics during actual injuries and during these tasks cannot be made. In a laboratory setting, participants often constrain their movements, so it is challenging to predict how similar joint mechanics are between the tasks performed in a laboratory and during the actual sports. Case-control studies share similar laboratory based limitations to prospective-cohort studies, however, they also have other limitations important to consider. These studies examine currently injured participants performing tasks, as opposed to pre-injury. Due to this study design, it cannot be

determined as to whether these mechanical differences were inherent in these injured individuals pre-injury, especially given movement patterns are influenced by pain. Only prospective studies can truly determine biomechanical risk factors associated with ACL injuries and PFPS. Case-studies and case-control studies do not allow for the determination of risk factors associated with both ACL injuries and PFPS as there is no certainty regarding the presence of the observed biomechanics prior to the onset of injury. Regarding participants in the studies included in this review, the majority were adult females, resulting in a lack of evidence around injuries in males as well as adolescents. Other limitations include that only seven PFPS and eight ACL injury studies were reviewed.

## **Conclusions**

By evaluating several different study designs looking at knee injuries during high risk manoeuvres, we were able to obtain a holistic perspective of biomechanics associated with both ACL injuries and PFPS. Looking at different biomechanical research approaches allowed us to assess not only the mechanism of injury, but also to look for commonalities in biomechanics between injured and uninjured participants both prospectively and following injury to better understand biomechanics associated with both ACL injuries and PFPS. This approach allowed us to assess biomechanics across key time points including pre-injury, at the time of injury, and following injury. At the knee, increased abduction loading coupled with shallow flexion angles were the most common biomechanics present in both ACL and PFPS studies; at the hip, increased flexion was most common across studies. Regarding the knee, these biomechanics were seen both pre-injury and at the time of injury. At the hip, increased flexion was observed at the time of injury and following injury. By focusing on prospective studies to outline common biomechanical risk factors in conjunction with biomechanics associated with these injuries at the time of injury, and following injury, better prevention programs can be developed. Previous literature has recognised these injuries as being risk factors for future injuries (122), so by determining the biomechanics that are associated with these injuries not just prior to, but during and following injury, we can establish programs that focus on correcting these mechanics during the associated high risk manoeuvres in order to decrease the risk of future injury. Programs focusing not just on neuromuscular training, but also skill specific training focused on correcting mechanics during these high risk manoeuvres may be of the greatest benefit regarding prevention. Future research should consider the impact

of cumulative loading on knee injury risk, specifically cumulative load in the frontal plane. Additionally, better techniques for assessing mechanics in-game are needed in order to facilitate injury prevention and screening strategies.

## **CHAPTER 3: MEASURING LOWER LIMB CUMULATIVE LOAD FOR INJURY PREVENTION IN SPORT.**

This chapter comprises the following paper to be submitted to the International Journal of Sports Physiology and Performance:

Weiss, K., McGuigan, M., Whatman, C., & Besier, T. A novel approach to measuring cumulative lower extremity load in sports. *International Journal of Sports Physiology and Performance* (in preparation).

### **Abstract**

Lower limb injuries are common in sport and have a mechanical aetiology, either via acute or chronic loading to musculoskeletal tissue. Cumulative loading is important to the onset and severity of injuries such as fatigue fracture or tendinopathy, but is difficult to measure in the field. Having a field-based, simple method to quantify and monitor mechanical loads may be the first step in the prevention and management of lower limb musculoskeletal injury. Furthermore, concepts of musculoskeletal mechanobiology should be integrated within the load measurement system to account for tissue adaptation. Musculoskeletal tissue is influenced by mechanical loads, such that the loads can either be positive, leading to enhanced structural integrity; or harmful, resulting in injuries or disease. To effectively measure and monitor lower limb cumulative loads in sport, mechanobiology principles should be integrated with load measurement as part of the surrogate metric. The purpose of this paper is to review the influence of cumulative lower limb mechanical load on musculoskeletal tissue homeostasis and injury risk, and examine appropriate methods to quantify cumulative lower limb load in the field.

### **Introduction**

Lower limb injuries are common in sport and damage to musculoskeletal tissue is invariably due to mechanical factors. Understanding the mechanical aetiology of sports injuries is critical to identify and prescribe appropriate interventions for prevention and rehabilitation (84). It has been suggested that both under and over-loading musculoskeletal tissue can increase the risk of injuries (43). However, to determine the optimal load stimulus which promotes maximal beneficial tissue adaptations at the lowest risk of injury, it is important to use a metric that reflects the



mechanobiological principles of tissue adaptation in conjunction with an effective, field-based load measurement system.

Evidence exists for both acute and chronic loads as causative factors in lower extremity injuries in sport. Knee ligament injuries, for example, occur when the mechanical loads applied to the ligament exceed the mechanical strength of the tissue, often during sudden acceleration-deceleration movements, jumping and landing, and change in direction (70). PFPS and ACL injuries are examples of common injuries (25, 71) that have been associated with specific, load-based mechanical factors (123). Other mechanical, load-related injuries include tibial fatigue fracture (124), common in runners, and Achilles and patellar tendinopathy which is prevalent in racquet sports, track and field, volleyball, basketball and soccer (125, 126). Injuries including ACL ruptures and muscle-tendon strains are often attributed to acute lower limb loading, while PFPS and tendinopathies are linked to repetitive, fatigue-induced, or cumulative lower limb loading (36-38).

The relationship between mechanical loads and musculoskeletal injuries is best understood through the principles of mechanobiology. The sport training and competition mechanical loads imposed on the musculoskeletal tissue stimulate homeostatic responses and physiological (i.e. structural) adaptations within the musculoskeletal tissue (28, 127). It has long been suggested that this balance between mechanical loads and the musculoskeletal tissue's ability to attenuate or respond to loads is a key causative factor in the development of injuries (128, 129). If tissue loads are in excess of the tissue's capacity, microdamage can accumulate, and potentially lead to macroscopic failure (24, 28). This type of cumulative load injury mechanism has been linked to injuries including bone fatigue fracture (often termed 'stress fracture' in the literature) (130) and tendinopathies (28, 131). To quantify cumulative mechanical loads placed on the musculoskeletal tissue of athletes, principles of mechanobiology should be incorporated into field-based load monitoring.

Different methods for measuring and monitoring mechanical lower limb loads have been used to evaluate kinematic (e.g. joint angle) and kinetic (e.g. joint moment) variables associated with injury risk (56, 132). Kinematic assessment of various sporting tasks is often assessed in a laboratory using 3D motion capture. Ground reaction forces collected from force plates can then be integrated to estimate joint moments using an inverse dynamic approach, which serves as a surrogate measure for

joint and tissue loading. However, traditional, laboratory-based analyses are expensive and time consuming. Additionally, they capture only a snapshot of a few tasks and do not take into account aspects such as fatigue damage to musculoskeletal tissues, related to the cumulative loads experienced by the tissue. Further, movements are often constrained in the laboratory and do not truly replicate those during games or training.

Due to the limitations of laboratory based load measures a need for simple, reliable, and effective field-based methods to measure mechanical load has been identified (24, 56, 133). Additionally, authors have suggested distinguishing between measures of external load and internal load (43). External load as it pertains to the literature on sports injury considers the physical work done by the athlete, quantified by measures such as distance covered, whole body accelerations, jump counts and intensity of sprints (45, 56, 134-136). Internal load in this context is considered the response of the athlete to the external load measured for example by heart rate or perceived exertion. These measures of external and internal load have been linked to general injury risk and are useful indications of physical exertion, types of tasks and training and game demands (137, 138). However, they may not be the most effective methods for measuring cumulative load experienced by the musculoskeletal tissues.

To quantify lower limb musculoskeletal tissue mechanical loads, field based measurement from the lower limb and tissue-level stress-strain should be considered as part of the surrogate metric. The purpose of this paper is to (i) review the influence of cumulative lower limb mechanical load on musculoskeletal tissue homeostasis and injury risk, and (ii) explore appropriate methods to quantify cumulative lower limb load in the field.

## **The influence of cumulative lower limb mechanical load on musculoskeletal tissue homeostasis and injury**

Musculoskeletal tissue is influenced by the loads imposed upon it such that the tissue structurally adapts to maintain homeostasis (24). In addition to maintaining homeostasis, mechanical loads (or lack thereof) are also responsible for detrimental effects on musculoskeletal tissue, resulting in injury or disease. Tissue injury most often manifests when the loads imposed on the tissue surpass the tissues' mechanical strength. Mechanical loads can cause acute failure, attributed to a single loading incident that results in structural failure (e.g. ligament rupture, or broken bone); or they can be overuse, where cumulative, repetitive loads lead to fatigue damage, ultimately

resulting in structural failure (24, 133, 139).

Overuse lower limb injuries are defined as the consequence of repetitive micro-trauma to the musculoskeletal tissue (140) where the pain presents during exercise and has no known incidence of trauma or disease that may have produced previous symptoms (141). Having a simple and reliable method for monitoring and quantifying cumulative mechanical loads may be of great benefit to identify when the cumulative micro-trauma exceeds that which the tissue can naturally recover from, which may result in overuse injury. By monitoring mechanical loads within the context of musculoskeletal tissue mechanobiology, we can develop an understanding of the importance and influence of cumulative loads and their relationship to injury and rehabilitation.

Monitoring counts of repetitive tasks has been suggested as an option for quantifying lower limb loads and associated injury risk (142). For example, counts of jumps in volleyball and other jumping sports has been recommended as a means for monitoring lower limb loads (142). However, a simple count of tasks may not indicate whether the mechanical loads being imposed on the tissue are resulting in positive or negative structural adaptations as they are not indicative of the magnitude or type of loading the tissue experiences. Within the musculoskeletal system, it has been established that there is a direct relationship between the structure and function of musculoskeletal tissue (140). Carter & Beaupré (143) describe a physical order that manifests in the various musculoskeletal tissues at the levels of organ, tissue, cell, and molecule that is regulated by biological processes and mechanical forces,(143). Mechanical forces need to be understood in the context of normal tissue function and injury and it is clear that simple counts of tasks do not account for the magnitude of these forces.

The envelope of function, proposed by Dye (24) describes this important relationship between the mechanical loads experienced by a joint and the homeostasis of the joint. To maintain healthy tissue, or tissue homeostasis, a sufficient amount of mechanical loading is required (which is represented by load magnitude and the frequency or cycles of these loads). Repeated loads without adequate periods of recovery can decrease the load range in which tissue homeostasis can be maintained, resulting in greater risk of tissue damage (24, 144, 145). However, large loads accompanied by sufficient periods of recovery lead to beneficial tissue adaptations. To

keep athletes performing at maximal effort with minimal risk of musculoskeletal injuries, it may be beneficial to monitor the cumulative tissue load to determine their zone of homeostasis. Using knowledge of cumulative load, athletes could monitor their training bouts in terms of their individual zones of homeostasis and potentially reduce the risk of fatigue-related lower limb injury.

Mechanical loads that act on the musculoskeletal tissue drive the adaptation response of the tissue. The envelope of function is regulated by mechanical and physical conditions that determine musculoskeletal tissue biological processes, such that mechanical loading and musculoskeletal tissue structure and adaptation are strongly linked (140). Bones, cartilage, tendons, ligaments, and muscles adapt with respect to the mechanical loads imposed on them (146-149). With regard to bone, Wolff's law refers to the functional adaptation of tissue to mechanics (150). For bones, micro-strains can lead to tissue adaptation, where additional bone is added to the areas that endure the largest loads, such as those experienced during dynamic sports tasks like landing from a jump, acceleration, and deceleration (151). Likewise, if there are areas under-loaded (due to immobilisation), bone reabsorption may occur (152, 153). With respect to the knee joint, the cartilage and bone becomes accustomed to the mechanical loading and number of load cycles occurring during locomotion, and the homeostasis of this healthy cartilage [and bone] is sustained as long as there are no alterations to the normal patterns of locomotion, the knee joint's structure, or the cartilage [and bone] biology (154). The two mechanical pathways that result in knee osteoarthritis include long-term repetitive wear combined with friction; and, instantaneous loading (155). Tendons also respond to load by adapting in order to withstand the loading environment (156). As a result of reasonable mechanical loading, tendons can increase both cross sectional area and tensile strength via fibroblasts that increase production of collagen type I (157). In contrast, abnormally high cumulative loading can lead to overuse injuries and tendinopathy (158, 159). Similarly, ligamentous structures adapt as a result of mechanical stimuli (160). Ligament injuries can result from an acute load that supersedes its maximal strength, as well as from cumulative loading. Repetitive load in conjunction with inadequate recovery time, leads to chronic stresses that can manifest as an acute tear or rupture. Additionally research in ACL injuries has determined that increased repetitive loading resulting from poor mechanics increases the stress acting on the ligament, which leads to increased injury risk (73).

To measure cumulative lower limb load, an appropriate metric is required which takes in to account the association between the musculoskeletal tissue and mechanical load. The daily load stimulus (DLS), is a metric of cumulative load which describes the relationship between mechanical load stimuli and bone remodelling as a function of the stimulus (161). This DLS is the product of the magnitude of the loads and the number of load cycles (or frequency) of these loads.

$$\text{Daily Load Stimulus (DLS)} = [\sum \sigma^m \cdot n]^{1/m}$$

The symbols represent the following:

$\sigma$       effective stress (or strain) per loading condition  
 $n$         number of loading cycles per loading condition  
 $m$         weighting factor

The load magnitudes are weighted to account for the greater influence the magnitude of the strain has on the bone tissue relative to the impact of the frequency/number of load cycles (161). The sum of all of the products of the varying loads and their cycles provides a total load stimulus, or cumulative load. There are currently multiple iterations of the DLS model (161-166). Each of these iterations have been created and used for different applications. Some of these applications include the estimation of the osteogenic response of bone to varying amounts of daily activity (164, 167). These estimate the efficacy of exercised-induced loading to offset bone loss resulting from microgravity (163), and the use of a load magnitude based formula looking at the rate of fatigue damage accretion and its impact on the initiation of bone remodeling (165, 166, 168). It has also been suggested that this approach for quantifying the total daily load stimulus (cumulative load) is not restricted to bone remodelling theory, and it may also be applied to any energy-based remodelling measure (such as load strain for other musculoskeletal tissue, e.g. cartilage, tendons, and ligaments) (169). Overuse injury risk may be better identified by the use of a suitable mathematical metric that accounts for the underlying mechanobiology of the tissue in conjunction with a simple monitoring tool to quantify cumulative loads. This metric may also allow more specific training strategies for each athlete benefiting performance.

### **The possible benefits of measuring cumulative load using an adapted tissue strain mathematical model**

The advent of wearable sensors for measuring and monitoring load provide the capability to assess athletes' outside of the laboratory and allow users to calculate

metrics of cumulative loading during actual training and matches. A number of different wearable sensors have recently been developed and used in sport to monitor variables such as speed, position, and external mechanical load (135, 170-172). Global positioning systems (GPS) have been integrated into these wearable sensors to detect speed and distance travelled by individual athletes during training and match situations. While informative, these data may not be effective in monitoring loading (specifically in the lower limbs), as distance and speed travelled do not directly represent the load imposed on the musculoskeletal tissue in the lower limbs. Given the large amount of force attenuated by the ankle, knee, and hip joints, loads estimated via wearable sensors in the upper body can significantly underestimate impact loads experienced in the lower limbs (173). Therefore, monitoring loading with inertial sensors located on the trunk is unlikely to reflect loads imposed on the musculoskeletal tissue in the lower limbs. Furthermore, without taking into account the relationship between the load magnitude and tissue stimulus, the estimates of cumulative load will likely be skewed if it is based on counts of impacts, speed, or distance measures alone.

Therefore, the use of wearable sensors such as accelerometers, worn bilaterally on the antero-medial tibia, may be a more appropriate placement in terms of measuring and monitoring lower limb loads (173-175). Accelerometers placed on the tibia allow for the measurement of tibial shock, or peak impact accelerations, which can function as a proxy measure of the loads experienced by the underlying musculoskeletal tissue (173, 174, 176, 177). This simple, non-invasive method has been used across studies looking at impacts in landing, running, and walking tasks (178-184). In particular, several studies sought to investigate shock attenuation during these tasks as it may be a critical factor with respect to an individual's risk of injury (173, 174). In a study by Zhang et al. [78], the authors looked at shock attenuation during landing from various heights using accelerometers on the tibia and head. Much larger impact accelerations were measured at the tibia, indicating that loading may have been largely mitigated by the lower extremities (173). Measuring tibial shock in conjunction with an appropriate model for quantifying cumulative loads, may be more beneficial in the monitoring of loading that may increase the associated risk of lower limb injuries. This may be useful in implementing and assessing changes in technique during numerous sports tasks to reduce peak impact loads. Other applications include monitoring injury recovery and intervention strategies as load is reintroduced in order to get athletes back to their baseline loading.

## **Conclusion**

Musculoskeletal tissue is influenced by its local mechanical environment. Mechanical loads imposed on the tissue can be beneficial, leading to adaptation and the maintenance of homeostasis, or, they can be harmful leading to injuries as a result of structural failure. By understanding the mechanical environment of the musculoskeletal tissue and its response to loading, and accounting for this, more appropriate load measures can be developed. The daily load stimulus serves as a more reasonable estimate of the loads experienced by the musculoskeletal tissue than counts of tasks, speed, distance, or acceleration/deceleration measures. It is not just the frequency of loads, but also their magnitudes, which are responsible for the musculoskeletal tissue's response to load. To quantify the loads experienced by the musculoskeletal tissue in the lower extremities, it is also important to place the inertial sensors in a location that will most accurately represent these loads. Bilateral sensors placed on the distal tibia provide a surrogate measure of loads experienced by the underlying bone. This proposed method allows for a simple and reliable means for monitoring and measuring lower limb cumulative loads in athletes across a variety of sports.

## **CHAPTER 4: THE APPLICATION OF A SIMPLE SURVEILLANCE METHOD FOR DETECTING THE PREVALENCE AND IMPACT OF OVERUSE INJURIES IN PROFESSIONAL MEN'S BASKETBALL.**

This chapter comprises the following paper accepted for publication in the Journal of Strength and Conditioning Research:

Weiss, K., McGuigan, M., Besier, T., & Whatman, C. (2017). The application of a simple surveillance method for detecting the prevalence and impact of overuse injuries in professional men's basketball. *Journal of Strength and Conditioning Research*.

### **Abstract**

The aim of this study was to use the OSTRC overuse injury questionnaire to record overuse injuries over a single season for a men's professional basketball team in order to; (i) assess the prevalence and severity of overuse injuries and (ii) determine the efficacy of this method in identifying overuse injuries in comparison to the team physiotherapist's detection of these injuries. Thirteen athletes from a men's professional basketball team participated in this study. The self-reported, OSTRC injury questionnaire was used to record overuse conditions of the ankle, knee, lower back over an entire 24-week season. Standard time loss injury registration methods were also used to record overuse conditions by the physiotherapist. Overuse injury rates per 1000 hrs of athlete exposure and average weekly prevalence of overuse injuries were calculated using the results of the questionnaire. A total of 183 overuse conditions were identified by the questionnaire, whereas only 28 overuse conditions were identified by the physiotherapist. The team's average weekly prevalence of all overuse conditions was 63% (95%CI:60-66) with the highest prevalence of injury affecting the lower back (25.9% [95%CI:19.7-32.1]). The overuse injury rate per 1000 hrs of athlete exposure was 6.4. The OSTRC overuse injury questionnaire captures many more overuse injuries in basketball than standard time loss methods. The prevalence of lower back injuries is higher than previously reported in basketball. This additional method of overuse injury surveillance may more accurately quantify the overuse injury problem in basketball and aid earlier intervention and management of these conditions.

### **Introduction**

Basketball is an extremely popular sport played throughout the world (1, 185).



Among non-contact sports, basketball has the highest incidence of injuries, with some research noting it to have a higher risk of injuries than many contact sports (8, 9). The most common injuries in basketball are reported to involve the ankles, knees, and lower back (11-14). Across the literature, injuries to the knee have been shown to have the greatest impact due to time-loss in sport (14, 15, 186). Additionally, overuse injuries, where there is no specific event attributed to the onset of the injury, are considered the primary injury type in sports such as basketball and volleyball that involve a lot of repetitive jumping and landing (10). However, the magnitude and severity of the overuse injury problem in sports is poorly understood (66, 67). Accurately quantifying this is important as successful sports teams typically have the largest number of athletes available to compete and lower injury problems than less successful teams. On many teams, athletes will continue to participate in training and matches despite experiencing pain and decreased function due to an overuse injury (64, 187). As a result, the standard time-loss definition of injury used in many studies may largely underestimate the number of overuse injuries and the impact this is likely to have on team performance.

According to the model outlined by van Mechelen et al. (84), the first step in sports injury prevention research is to describe the magnitude of the injury problem. Without an adequate method for effectively determining the magnitude of overuse injuries, it is difficult to move forward in terms of developing injury prevention measures or proactively manage injuries in a team setting (64). In a sport such as basketball, where athletes typically play approximately 82 games over a 6-month season, the impact of overuse injuries on the athletes is likely to be significant and have an overall negative impact on the team. However, there is a lack of data describing the prevalence and severity of overuse injuries in the sport. To assess the magnitude of these overuse injuries, an effective method for injury registration is required (64). Previously, the literature has used a variety of different definitions with respect to injuries. As noted earlier time-loss is the most common, defining injuries as events resulting in at least one missed participation (14, 15, 188). Definitions for overuse injuries have been proposed using self-perceived pain and/or stiffness that occurred during and/or following basketball training or matches and continuing for a minimum of three basketball activity days (189). Most recently, the OSTRC has published an overuse injury questionnaire (68), which has been found to be an effective method for registering overuse injuries across a number of sports including tennis, cycling, floorball, handball, volleyball, and cross country skiing (63, 69). This self-reported

questionnaire is completed once each week by each athlete over the course of their season. It is an attractive tool for practitioners as it is a simple, cost effective approach to athlete monitoring, which is key to practical implementation (190-194). Research examining the effectiveness of monitoring athletes through self-reported questionnaires has suggested that the measurement used should be inclusive of a design that is able to generate quality and important data with negligible inconvenience to the athlete (192). Additionally, it has been suggested that a number of these injuries are preventable (43). By having a simple, effective tool for identifying injuries, practitioners may be able to more effectively prescribe training loads and manage the impact of injuries on their athletes.

Thus, the aim of this research was to use the OSTRC overuse injury questionnaire to record overuse injuries to the ankle, knee, and lower back across a single season for a men's professional basketball team in order to; (i) assess the prevalence and severity of overuse injuries and (ii) determine the efficacy of this method in identifying overuse injuries in comparison to the team physiotherapist's detection of these injuries.

## **Methods**

### **Experimental Approach to the Problem**

This was a prospective cohort study over the entire basketball season (September 2015 to February 2016). A self-reported overuse injury questionnaire, the OSTRC Overuse Injury Questionnaire (68), was sent electronically to all athletes in the study once a week over the 24 week season while a parallel registration of injuries was also conducted by the team physiotherapist using standard methods of injury registration based on time-loss (195).

### **Participants**

Thirteen athletes from a men's professional basketball team (mean  $\pm$ SD; age, 24.4  $\pm$ 4.7 years; age range, 20-33 years; height, 195.0  $\pm$ 7.6 cm; body mass, 96.3  $\pm$ 11.6 kg; competitive experience, 5.9  $\pm$ 3.6 years) participated in this study. Athletes were verbally informed of the purpose and procedures of this study during the team preseason intake and testing. The university ethics committee approved the study. Informed consent was obtained from all individual participants included in the study.

## Procedures

Online survey software (Googledocs, California) was used to administer the OSTRC Overuse Injury Questionnaire (68) to all athletes in the study once a week over the 24-week season. A group text reminder was sent by the team physiotherapist to the athletes every Sunday to ensure as many athletes as possible completed the questionnaire every week. The questionnaire consisted of four questions for each anatomical area of interest (ankle, knee and lower back) (68). For each week, a severity score was obtained ranging from 0 to 100 for all reported overuse symptoms based on the summation of the athlete's responses to the four questions (196). Each response to the four questions was assigned a value ranging between 0 and 25, with 0 being the equivalent to no problems and 25 the maximum value for each question. For questions 1 and 4, the response scores were 0-8-17-25, and questions 2 and 3 were scored 0-6-13-19-25, as determined by the questionnaire developers (68). Scores were used to evaluate how the overuse symptoms progressed week to week. The complete questionnaire for the knee can be seen in Figure 4 and this was adapted for the ankle and lower back. All athletes were contacted by the team physiotherapist on a weekly basis to review questionnaire responses to confirm whether the problem reported was acute or overuse in nature. Acute injuries were defined as those whose onset was connected to a specific inciting event, whereas overuse injuries were not related to a specific incident and were either gradual or rapid in onset (196). If an overuse injury was recurring in the same location, it was still treated as a single case in spite of periods where symptoms subsided. If the injury was acute, it was removed from the data (197). During this same time period, a parallel registration of injuries was also conducted by the team physiotherapist using standard methods of injury registration based on time-loss (195). Time-loss injuries were registered during scheduled team training and meeting times by the team physiotherapist following methods described in a consensus statement for injury surveillance methods in football (198). The outcome variables included: overuse injury symptom prevalence for each anatomical area; average weekly prevalence of overuse injury symptoms for each anatomical area; severe overuse symptom prevalence for each anatomical area; average weekly prevalence of severe overuse symptoms for each anatomical area; the rate of overuse conditions per 1000 hr athlete exposure using the questionnaire and the physiotherapist registered injuries separately.

Question 1: Have you had any difficulties participating in normal training and competition due to knee problems during the past week?

- ☐ Full participation without knee problems
- ☐ Full participation, but with knee problems
- ☐ Reduced participation due to knee problems
- ☐ Cannot participate due to knee problems

Question 2: To what extent have you reduced your training volume due to knee problems during the past week?

- ☐ No reduction
- ☐ To a minor extent
- ☐ To a moderate extent
- ☐ To a major extent
- ☐ Cannot participate at all

Question 3: To what extent have knee problems affected your performance during the past week?

- ☐ No effect
- ☐ To a minor extent
- ☐ To a moderate extent
- ☐ To a major extent
- ☐ Cannot participate at all

Question 4: To what extent have you experienced knee pain related to your sport during the past week?

- ☐ No pain
- ☐ Mild pain
- ☐ Moderate pain
- ☐ Severe pain

**Figure 4. The OSTRC overuse injury questionnaire.**

### **Statistical Analyses**

Means and standard deviations (SD) were determined for baseline demographics. Overuse symptom prevalence was determined for each anatomical area each week of the study by dividing the number of athletes that reported any symptoms (e.g. anything but zero in any of the four questions) by the number of questionnaire respondents. The average weekly prevalence of overuse symptoms was also calculated for each anatomical area over the course of the entire study (69, 196, 198). A secondary prevalence measure, the weekly prevalence of severe overuse symptoms, was also determined for each anatomical area as suggested by Clarsen et al. (68). This was calculated similar to the initial prevalence measure, however, the numerator

included only the overuse symptoms that resulted in moderate or severe reductions in training volume or sports performance, or the complete inability to participate (e.g. responding to questions 2 or 3 with the 3<sup>rd</sup>, 4<sup>th</sup>, or 5<sup>th</sup> option). A 95% confidence interval was also calculated of each of these prevalence measures. The data obtained from the first week of the study was removed and excluded from all calculations as suggested by Clarsen et al. (68).

## Results

A total of 13 athletes participated in the study. There was an average weekly response rate of 90% of athletes over the course of the study. Seven athletes (54%) completed all 24 questionnaires. A total of 28,738 hours of basketball exposure was reported throughout the 24-week season (a total of 2,211 hours of basketball exposure per player, with 1,949 hours during training and 262 hours during games). This equates to an average weekly training exposure per athlete of  $5.8 \pm 2.3$  hours (mean  $\pm$ SD total for season =  $140.0 \pm 3.1$  hours) and an average weekly playing exposure of  $0.8 \pm 0.7$  hours (mean total for season  $\pm$ SD =  $18.7 \pm 15.7$  hours).

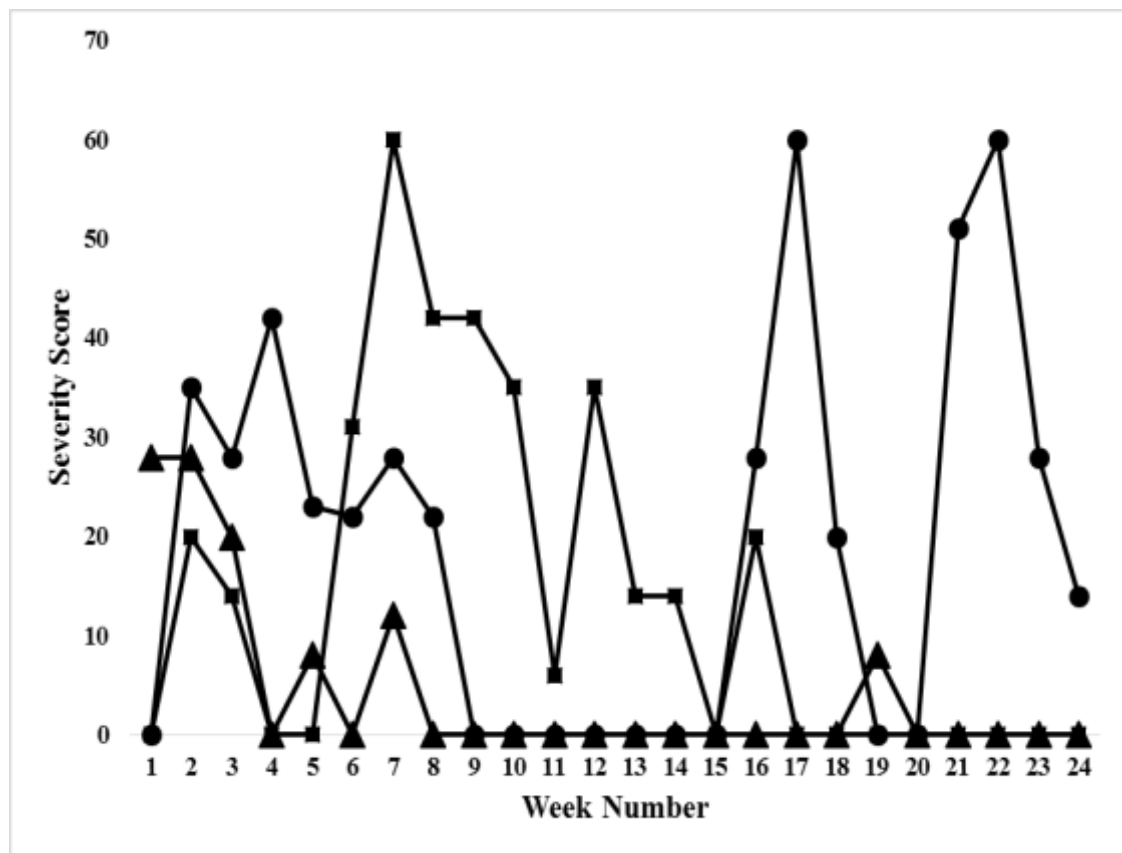
**Table 4. Mean weekly prevalence of overuse conditions. Mean (95% CI) weekly prevalence of all overuse conditions and severe overuse conditions affecting the ankle, knee, and low back based on the OSTRC injury questionnaire.**

	Ankle	Knee	Lower back
Average weekly prevalence (all problems) N=183	12.8% (10.0-15.6) N=37	24.4% (19.5-29.3) N=71	25.9% (19.7-32.1) N=75
Average weekly prevalence (severe problems) N=23	1.5% (0.2-2.8) N=4	3.2% (1.4-5.0) N=11	2.7% (1.0-4.4) N=8

Severe problem: overuse problem causing moderate/severe reductions in training volume or sports performance or complete inability to participate in training or games. N represents the total number of cases for the duration of the study.

A total of 183 overuse conditions were reported via the OSTRC overuse injury questionnaire across the 13 athletes in the study. All of the athletes in the study reported overuse conditions, with two athletes reporting three overuse conditions, and 11 athletes reporting four or more overuse conditions. For all of the reported overuse conditions, 23 (12.6%) were considered severe. The average weekly prevalence of all overuse conditions reported was 63% (95% CI:60 to 66) and of severe overuse

conditions 7.3% (95% CI:7.1 to 7.6) (Table 1. Mean weekly prevalence of overuse conditions). An example of the weekly OSTRC scores for a single individual over the 24-week season can be seen in Figure 5.



**Figure 5. Example of an athlete with the highest cumulative severity scores during the 24-week study. Circles: ankle severity score, squares: knee severity score, triangles: low back severity score.**

A total of 28 overuse conditions were registered by the team physiotherapist (based on a time-loss injury definition) for 12 of the 13 athletes. Based on this injury report from the physiotherapist only one athlete did not have any overuse conditions over the duration of the study, six athletes had one overuse condition, two athletes had two overuse conditions and five athletes had three or more overuse conditions. Additionally, the total number of ankle overuse conditions reported by the physiotherapist for the entire season was 11, knee overuse conditions was 15 and lower back overuse conditions was two. The rate of overuse conditions (per 1,000 hours athlete exposure) was higher based on the OSTRC questionnaire (6.4 injuries per 1000 hours) versus the physiotherapist diagnosis (0.97 injuries per 1000 hours).

## Discussion

This study demonstrated that the entire team experienced overuse injuries over the course of the season when classified by the OSTRC overuse injury questionnaire. Additionally, 6.5 times as many overuse problems were identified by the questionnaire in comparison to those registered by the team physiotherapist. During the season, a total of 85% of the athletes reported four or more overuse problems. Another major finding of this study was that approximately 62% of the athletes played each week despite the presence of overuse symptoms. Three specific anatomical areas, including the ankle, knee, and lower back, were investigated in this study. Despite the basketball injury literature identifying the ankle as the most frequently injured area (11-14), we recorded higher rates of lower back and knee conditions. This may be important due to its potential impact on injury prevention strategies as they may not accurately target the more prevalent overuse conditions requiring attention.

The total number of all reported overuse injuries was much higher in this study than in similar research looking at tennis (69), cross country skiing, cycling, floorball, handball, and volleyball (63). The average weekly prevalence of knee problems was similar to that previously reported in cycling, floorball, handball, and tennis, with only volleyball having a higher weekly prevalence, which is likely due to the fact that the sport involves the greatest volume of jumping and landing comparatively. Reported average weekly prevalence of overuse symptoms was much higher for the lower back in the current study in comparison to all of the aforementioned sports aside from floorball (63). The only previous study reporting average weekly prevalence for the ankle was in tennis and the findings were the same as our findings (69).

As mentioned earlier, in comparison to the ankle, the prevalence of knee and lower back overuse problems was higher in our study than in other basketball overuse injury literature. While overuse knee and back problems are frequently reported in the basketball literature, ankle problems are often reported as the most common. This may be related to the fact that many of the athletes routinely taped or wore braces on their ankles during all trainings and games, possibly helping to reduce overuse symptoms. As both the knees and the lower back were the problems representing the greatest overall impact on the athletes in this study, it is suggested that future attention be focused on prevention of overuse injuries to these areas.

With respect to severe overuse symptoms, the knee represented the greatest number of reported problems, followed by the lower back and the ankle. Our findings

indicate the prevalence of severe knee problems in basketball is relatively low in comparison to volleyball, cycling, and handball, while the prevalence of severe lower back problems was similar to other sports (63). None of the previous studies presented findings on average weekly prevalence of severe ankle problems.

The athletes in the current study continued to participate in training and games despite the presence of pain or varying performance limitations. This suggests that perhaps other more common forms of injury registration may misrepresent the true magnitude of overuse symptoms (64). The use of the OSTRC overuse injury questionnaire may be an more effective method for identifying and monitoring the prevalence of overuse problems as it is designed to detect overuse conditions, even if no absence from training or competition occurs (64). Furthermore, the self-reported questionnaire detected a larger number of overuse problems in comparison to those registered by the team physiotherapist. This finding suggests that this simple, self-reported questionnaire may be beneficial in identifying athletes experiencing overuse problems in team sports with a large number of athletes and/or a small medical staff. Having athletes determine whether or not they experienced symptoms may also be helpful in the elimination of systematic bias as well as consistency in tracking overuse injury data for a specific athlete across multiple seasons.

A strength of this study was the high average weekly response rate but there are limitations to this approach of using a self-reported questionnaire for overuse symptom monitoring which need to be considered. First and foremost, the efficacy of this method relies solely on the extent to which the athletes willingly and consistently participate. Though the majority of athletes in this study responded to the questionnaire each week, full participation was never consistently achieved across the season. This method may also be impacted by an athlete's cooperation in terms of providing honest appraisal of overuse symptoms via the questionnaire. If an athlete feels that their questionnaire responses may influence whether they are selected to play, they may not be willing to report overuse problems (68). Secondly, the injuries recorded were only those based on the pre-defined sites. In addition, injuries registered by the team physiotherapist using standard methods may have led to less overuse symptoms being identified. This may be attributed to the standard method's more generalized and open-ended style of questioning regarding overuse problems as opposed to a consistent and specific set of questions directed at the three anatomical areas of interest as used by the OSTRC questionnaire (65, 199).



## **Practical Applications**

The findings from this research include the prevalence and impact of overuse injuries in professional basketball. The methods used in the previous basketball injury literature were less effective surveillance strategies in comparison to the method used in this research. The OSTRC questionnaire is a simple, easily administered tool for overuse injury surveillance in basketball. It allows for a more accurate indication of the health status of athletes than time loss definitions, and suggests the injury problem in basketball is much greater than previously reported. This may be a more practical surveillance strategy in the team sports setting as it is more likely to reflect the current injury status and performance capacity of the team, which is important especially during key time points such as playoffs, where athletes may need to compete despite the presence of injury problems. Lastly, use of this questionnaire may allow for better prevention of overuse injuries. The ability to identify overuse conditions early allows for adjustments in training and treatment. This type of monitoring tool may also help with training load planning and implementation as changes such as the sudden presence of injury problems or changes in degrees of severity of problems are accounted for using this questionnaire. More informed decisions such as whether an athlete will compete during crucial points in the season may be facilitated by the data provided using the questionnaire. Using the questionnaire may be better for identifying injury patterns and help with evaluating the efficacy of recovery strategies, training, prevention interventions and rehabilitation protocols based on this data. In turn, more targeted prevention interventions and recovery modalities can be employed during training and competition blocks with higher rates of injury problems. It also detected a greater number of overuse injuries, meaning some athletes did not seek medical attention, perhaps because they are used to certain levels of pain and therefore didn't identify themselves as injured. This questionnaire provides a means of greater communication between athletes and medical staff, which may help in decreasing the number of overuse injuries. High injury prevalence is cause for concern as once a player sustains an overuse injury, they may not get an adequate period of time for recovery until the season ends. Primary prevention strategies should be focused around overuse injuries to the lower back and knees in basketball, as they appear most prevalent. These strategies may include focus on proper mechanics during jumping and landing and change in direction tasks. In addition to preventative training for common overuse injuries, it may also be beneficial to monitor cumulative external training loads (200). Frequent monitoring of cumulative loads may be useful in

conjunction with the OSTRC questionnaire for detecting changes requiring further attention.

The results of this research indicate that the prevalence of overuse injuries may be much greater in the lower back and knees in basketball than has been previously reported in the literature. This could be due to conflicting injury definitions being used to determine the magnitude of these overuse injuries in basketball. Inaccuracies in the reported magnitudes of overuse conditions using standard surveillance methods may be detrimental to the development of injury prevention strategies, as these protocols may be targeted at the areas which do not actually have the highest overuse injury prevalence. Further, much greater total number of overuse conditions were reported by the OSTRC questionnaire in comparison to the physiotherapist, indicating that a number of athletes suffering overuse conditions did not seek medical attention. By having a secondary method of overuse symptom surveillance, treatment and intervention strategies can be deployed earlier, potentially mitigating the impact and severity of the overuse conditions.

## CHAPTER 5: QUANTIFYING LOWER LIMB LOAD IN MEN'S PROFESSIONAL BASKETBALL TRAINING

This chapter comprises the following paper to be submitted to the International Journal of Sports Physiology and Performance:

Weiss, K., Allen, S., McGuigan, M., & Whatman, C. (2017). Quantifying lower limb load in basketball training. *International Journal of Sports Physiology and Performance* (in preparation).

### Abstract

**Aim** To use wearable accelerometers during professional basketball trainings to: (1) quantify lower limb steps per minute (steps/minute), step intensity, and lower limb loads per minute (load/minute) [using an adapted tissue load metric]; (2) investigate limb asymmetry in the context of steps/minute and load/minute; and, (3) examine differences in bilateral lower limb loads using counts of impacts versus the adapted tissue load metric.

**Methods** A single professional men's basketball team (N=13) wore bilateral accelerometers on their tibiae for a total of 180 minutes of training. The impact accelerations were binned into 2g increments ranging from 2 to 16g. The total counts of impacts were determined bilaterally for each of the binned magnitude ranges (low (2-<4g), moderate (4-<10g), and high (10-14<sup>+</sup>g)). Lower limb loads were calculated using an adapted tissue load equation. Limb symmetry was assessed using a mixed linear model procedure to examine differences between sides for counts and load.

**Results** The mean $\pm$ SD steps/minute in total, and for low, moderate, and high intensity impacts for the right and left limbs were right (total: 37 $\pm$ 8; low: 8 $\pm$ 2; moderate: 24 $\pm$ 5; high: 5 $\pm$ 2) and left (total: 37  $\pm$ 10; low: 7 $\pm$ 2; moderate: 24 $\pm$ 7; high: 5 $\pm$ 2). There were no substantial group mean differences between limbs. The number of steps/minute at moderate intensity were substantially higher than steps/minute at low and high intensities. All differences for steps/minute (total and across each intensity) for individual players were unclear. The mean $\pm$ SD lower limb loading rates (load/minute) for the right and left limbs were 133406 $\pm$ 38535 and 134791 $\pm$ 40223, respectively (unitless measurement/minute). There were no substantial group mean differences between limbs. There was large typical variation between limbs in

load/minute [coefficient of variation = 67.5% (90%CL;  $x/\div 1.6$ )] compared to steps/minute [coefficient of variation = 10.1% (90%CL;  $x/\div 2.0$ )].

**Conclusions** Due to the simplicity of examining steps/minute and intensities, this method could potentially be used for monitoring in both physical preparedness and injury risk models. This method allows practitioners to see total counts of steps/minute, step rate across load intensities, and bilateral differences in step rate across intensities which may facilitate management of training loads for individuals and teams. Our lower limb load metric provides a means for evaluating bilateral loads during training and may be more reflective of tissue load than counts of steps/minute. While there were no mean differences, the CV suggests a higher variation in load/minute than steps/minute, which warrants further investigation as to the implications of this variation for players. The load/minute metric can be used for monitoring daily, weekly, and acute:chronic training loads so as to inform training load prescription and implementation. Regular monitoring of individual player load may be the best way to use the measure to assist with the management of lower limb injury risk and recovery.

## Introduction

The dynamic nature of basketball places large physiological and physical stress on athletes (3, 49, 201). For coaches and other support staff, the primary goal is to maximise performance while minimising the risk of injuries. To achieve this, appropriate methods of monitoring load are required so that training and rehabilitation strategies can be developed to support these goals. A number of methods exist in the literature with respect to monitoring training loads in basketball such as the session rate of perceived exertion (sRPE) model, heart rate-based methods, (20, 49, 50, 202)  $VO^2$ , and accumulated load using wearable accelerometers (203). However, in basketball, there has yet to be a specific method that most effectively quantifies lower limb mechanical training loads using a single metric or term.

During sports such as basketball, an athlete's body is subjected to large impact loads each time their feet strike the ground (204). The body attenuates these impact loads via the musculoskeletal tissue (55, 205). Musculoskeletal tissue (bone, cartilage, tendon, ligament, etc.) is greatly influenced by these external mechanical loads, such that it will structurally adapt in order to maintain homeostasis [Oleson et al., 2002]. These loads can be advantageous, leading to increased structural integrity; or

detrimental, resulting in injury or the onset of pathology, including conditions such as tibial stress syndrome, tendinopathy, and osteoarthritis (206-208). In comparison to running and walking, landing tasks have much larger impact forces (178, 184, 209). Thus, in sports such as basketball, which involves a large volume of jumping and landing, an athlete may accumulate much greater lower limb loads over the course of a training or game than in sports primarily involving running tasks.

While a number of studies have evaluated mechanical loads (e.g. via distance ran, distance covered at various speeds, whole body movements via acceleration rate of change) in sports such as rugby, Australian football, and even basketball, none have examined these loads in the lower limbs, specifically with respect to musculoskeletal tissue adaptation principles (132, 203, 210). Wearable, tri-axial accelerometers are able to assess movement by means of impact acceleration magnitudes and their frequencies. Previous research in basketball has utilised wearable accelerometers on the lumbosacral region to determine external player load during games, training scrimmages, and basketball specific training drills (203). While this may be of interest to coaches in terms of quantifying the different training/game specific task demands imposed on the athletes, it is unlikely to provide the best indication of the mechanical loads imposed on the musculoskeletal tissue, particularly in the lower limbs, where the greatest number of basketball related injuries occur (11, 12, 14, 189, 211-213). Additionally, accelerometers placed on the lumbosacral region may not be best for quantifying lower limb loading, which may be of greater importance in the monitoring and assessment of physical preparedness and injury risk.

Since the majority of basketball injuries occur in the lower limbs, monitoring external mechanical load using accelerometers worn on the tibiae may more accurately quantify the loads imposed on the underlying tissue (14, 214). Additionally placement on the tibia allows investigation of differences in bilateral lower limb loading which may be implicated in injury risk (215, 216).

In addition to placement of the sensors to monitor load, it is also important to consider the metric used to quantify load. Previously, jump count has been recommended as a means of monitoring lower limb load volume (142), however, this approach does not factor in the magnitude of the impact loads experienced by the musculoskeletal tissue. It has been suggested that excessively large impact loads may lead to injuries to the musculoskeletal tissue including tendinopathies, joint pain, osteoarthritis, and medial tibial stress (139, 217). Both load volume and magnitude contribute to the total training load acting on the athletes; therefore, a monitoring

system that accounts for both is needed (28). A potentially useful method for monitoring load is the use of accelerometers to record counts of impacts and the associated intensities. The daily load stimulus is a metric of load that takes into account the magnitude of the loads and their frequency, as well as a weighting factor which suggests that different load magnitudes will impact the tissue differently (161). This mathematical model quantifies the adaptive response of bones as well as other musculoskeletal tissue with respect to the mechanical stimulus resulting from weight bearing activities. It may serve as a good model for evaluating the impact of basketball training on the musculoskeletal tissue in the lower limbs (218).

The aims of this research were to use wearable accelerometers in professional basketball trainings in order to: (1) quantify lower limb steps per minute (steps/minute), step intensity, and lower limb loads per minute (load/minute) [using an adapted tissue load metric]; (2) investigate limb asymmetry in the context of steps/minute and load/minute; and, (3) examine differences in bilateral lower limb loads using counts of impacts versus the adapted tissue load metric.

## **Methods**

### **Participants**

Thirteen athletes (mean  $\pm$  SD; age,  $24.4 \pm 4.7$  years; height,  $194.9 \pm 7.6$  cm; body mass,  $96.3 \pm 11.6$  kg; competitive experience,  $5.9 \pm 3.6$  years) from one professional men's basketball team participated in this study during one Australia New Zealand Basketball League season (2015-2016). Athletes were given a clear explanation of the study and written consent was obtained. Experimental procedures were approved by the Auckland University of Technology Ethics Committee.

The athletes wore bilateral, tri-axial accelerometers (IMeasureU Ltd., Auckland, New Zealand) on the anteromedial aspect of their tibiae (one third of the distance between the medial malleoli and tibial plateau) (173, 175, 184) for a total of 180 minutes of basketball training. The accelerometers were placed so as to measure tibial shock (i.e. peak resultant impact accelerations) which was used as a surrogate measure of impact loads experienced by the underlying musculoskeletal tissue (173, 184). The peak resultant impact accelerations have been identified as more reliable than single axis impact accelerations in running at varying speeds (219). To limit potential soft-tissue artefacts, the sensors were attached firmly on the tibia (as close to the bone as possible) using sports tape (Artech cohesive bandage, 7.5cm). The accelerometers

sampled and data logged at 1000 Hz and were synchronised via a proprietary algorithm (IMeasureU Ltd., Auckland, New Zealand).

### **Data analysis**

Using a custom MATLAB script (Mathworks, MA, USA), the impact accelerations were binned into 2g increments ranging from 2 to 16g. The total counts of impacts were determined bilaterally for each of the binned magnitude ranges (low (2-<4g), moderate (4-<10g), and high (10-14<sup>+</sup>g)). Bilateral step rates were then calculated at each intensity for each player and as team means $\pm$ SD, by dividing these counts by 180 (total number of training minutes). Lower limb load was calculated using the daily load stimulus equation (165, 166):

$$\text{Daily Load Stimulus (DLS)} = [\Sigma (\sigma)^m (n)]$$

The symbols represent the following:

- $\sigma$  the effective stress (or strain) per loading condition (peak impact accelerations)
- $n$  the number of loading cycles per loading condition (counts of impacts at each magnitude)
- $m$  the weighting factor

This particular expression was chosen as it is strongly related to daily loading history where fatigue damage accretion as the result of stress is used in lieu of strain (162, 165). The above equation represents the loading potential in comparison to the rate of fatigue micro-damage as used previously in research looking at bone remodeling as a result of overload (166). The value of  $m$  was selected as four in alignment with prior studies (153, 161), specifically previous research examining how loading resulting from marathon training impacted the femur in terms of bone density, micro damage, and remodeling (165).

The total counts of impacts were determined by calculating the sum of the number of impacts ( $n$ ) for each loading condition (as described by the Daily Load Stimulus equation). The loading ratio between the athletes' right and left lower limbs was calculated to determine differences in bilateral loading profiles.

### **Statistical analysis**

Means and standard deviations were determined for the team and individual bilateral lower limb loads using the Daily Load Stimulus [adapted tissue load metric]. This was then expressed as rate (load/minute). Mean count of steps/minute was also

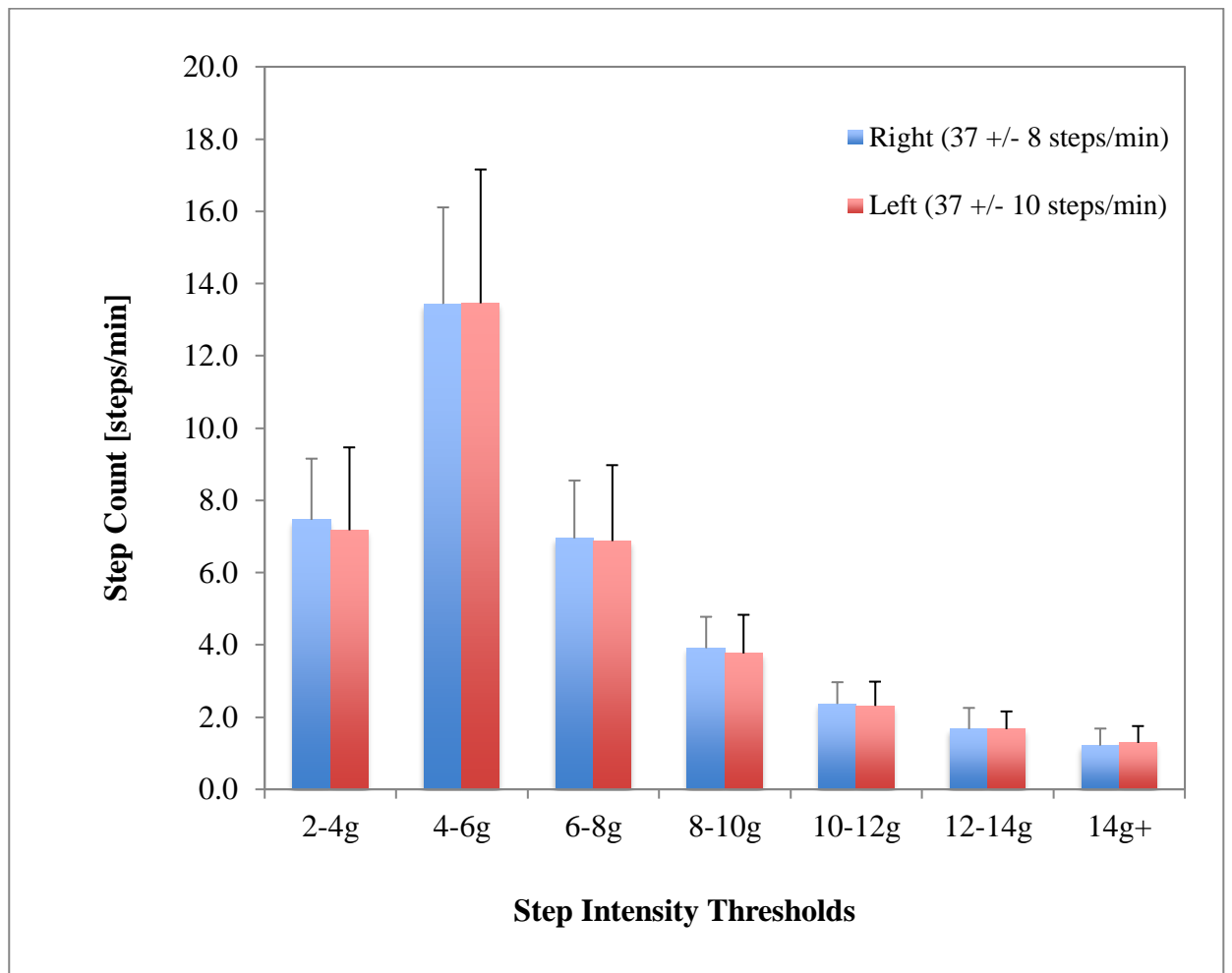
calculated bilaterally.

Step counts and load were log transformed for analysis using the mixed linear model procedure [proc mixed] in the Statistical Analysis System (Version 9.4, SAS Institute, Cary, NC). The model included fixed effects to estimate mean differences between limbs. A random effect was included to represent differences between limbs for each individual player. We used non-clinical magnitude-based inferences to assess these differences (Hopkins, Marshall, Batterham, and Hanin, 2009), whereby the smallest important difference was the average of the right and left standard deviations multiplied by 0.2. Thresholds for moderate, large and very large differences were (0.6, 1.2, and 2.0) of this average. Uncertainty in mean differences was expressed as 90% confidence limits and as likelihoods that the true value of the effect represents a substantial difference between limbs (Batterham & Hopkins, 2006). Where the effect had a >5% probability of being substantially positive and a >5% probability of being substantially negative the inference was stated as 'unclear' (220).

## Results

Mean $\pm$ SD steps/minute in total and for low, moderate, and high intensity impacts for the right and left limbs was right (total: 37 $\pm$ 8; low: 8 $\pm$ 2; moderate: 24 $\pm$ 5; high: 5 $\pm$ 2) and left (total: 37  $\pm$ 10; low: 7 $\pm$ 2; moderate: 24 $\pm$ 7; high: 5 $\pm$ 2). The histogram (Figure 6) displays the team mean steps/min at each 2g increment for the right and left limbs. Group mean differences between limbs were likely trivial (mean,  $\pm$ 90%CL= 0,  $\pm$  2 steps/minute). However, the number of steps/minute at moderate intensity were most likely greater than steps at low intensities (mean,  $\pm$ 90%CL= 16,  $\pm$ 3 steps/minute; large difference) and high intensities (mean,  $\pm$ 90%CL= 19,  $\pm$ 3 steps/minute; very large difference). Steps/min at low intensity were also possibly greater than step rates at high intensity (mean,  $\pm$ 90%CL = 2,  $\pm$ 1 steps/minute; small difference).

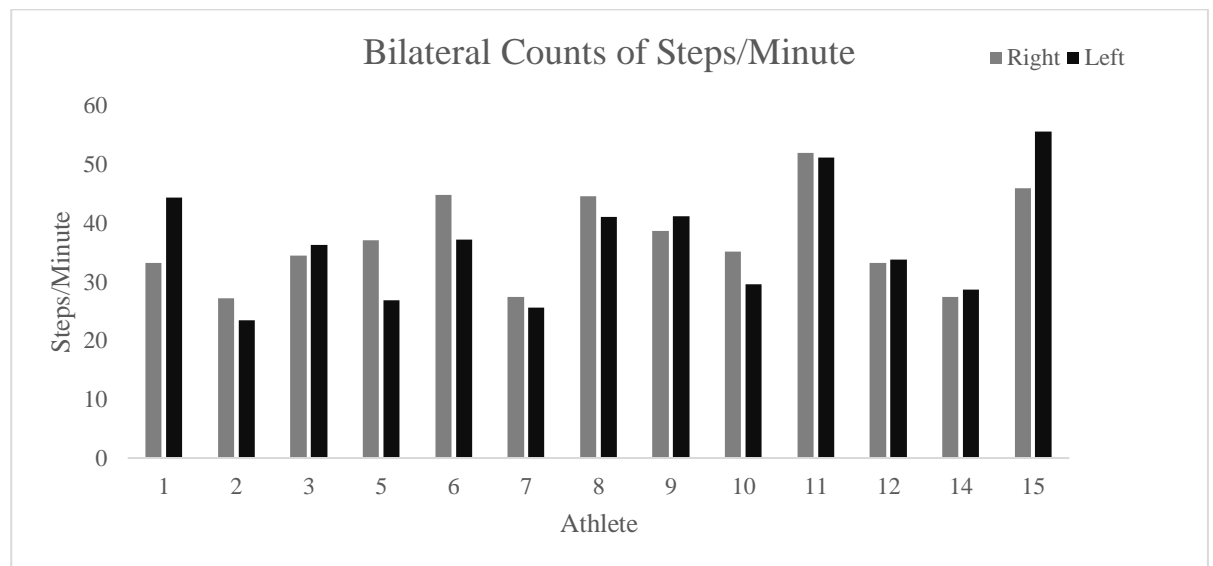




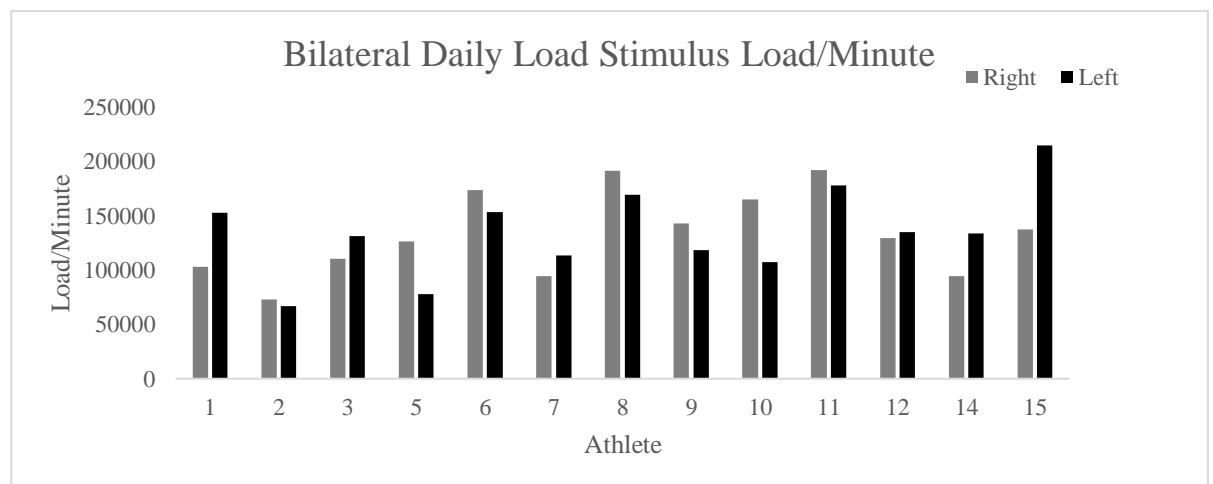
**Figure 6.** The histogram displays the team mean steps/min and standard deviations for the right and left limbs at each of the binned intensities. The legend mean steps/min and standard deviations are for the summed steps/min for all of the intensity bins. The low intensity thresholds are from 2-<4g, the moderate intensity thresholds range from 4-<10g, and the high intensity thresholds range from 10-14<sup>+</sup>g.

For individual comparison between limbs, the smallest worthwhile difference of 0.2 of the between subject standard deviation in steps/minute was 1.8. All differences for steps/minute between limbs for individual players were unclear. The random effect for limb provided a coefficient of variation (CV) of 10.1% (90%CL;  $x/\div 2.0$ ), representing the typical amount of variation between limbs within the different players. Figure 7(A) displays the individual total (across all three intensities) mean steps/minute bilaterally.

The team bilateral lower limb load/minute (mean  $\pm$ SD) for the right and left limbs was  $133406 \pm 38535$  and  $134791 \pm 40223$  respectively. There were no substantial group mean differences in load/minute between limbs. For individual comparison between limbs, the smallest worthwhile difference of 0.2 of the between subject standard deviation in load/minute was  $1.1 \times 10^{12}$  load/minute. The random effect for limb provided a CV of 67.5% (90%CL;  $x/\div 1.6$ ), representing the typical amount of variation between limbs within the different players. Visual interpretation of Figure 7 appears to show differences in the bilateral comparison when considering steps/minute versus load/minute for players 7, 9, 10, and 14 (Figure 7. (A) and (B)).



(A)



(B)

**Figure 7. (A) The mean bilateral counts of impacts steps/minute, and, (B) the mean bilateral lower limb load/minute using the Daily Load Stimulus Metric.**

## Discussion

This research sought to use wearable accelerometers in professional basketball trainings in order to: (1) quantify lower limb steps per minute (steps/minute), step intensity, and lower limb loads per minute (load/minute) [using an adapted tissue load metric]; (2) investigate limb asymmetry in the context of steps/minute and load/minute; and, (3) examine differences in bilateral lower limb loads using counts of impacts versus the adapted tissue load metric.

### *Counts of impacts*

The main findings indicate that on average the greatest steps/minute occur at moderate impact intensities. The results for comparisons between limbs for individuals were unclear, therefore, more data is required to investigate differences between limbs within individual players. Even though there were no substantial differences for individual means between sides, the high CV indicates that there is potentially substantial variation within individuals, and this is a valuable direction for future research. However, variability was observed not only between individuals, but also in bilateral load profiles within individuals across low, moderate, and high intensities. Practically, the data derived from this method of external load quantification may be most useful in prescribing specific training loads to increase physical preparedness, as well as monitoring for individual changes in bilateral external loads (e.g. steps/minute at each intensity).

External load monitoring is important for coaches and practitioners to understand, as it can help them better understand their athletes' work capabilities and monitor their training loads in order to prevent them from getting injured. When analyzing the group data, the mean data for the team provides an overall indication of the distribution of impact intensities resulting from regular basketball training sessions. Our group data shows that the majority of steps/minute occurred at moderate intensities. Monitoring changes in steps/minute may allow for more appropriate week to week increases in intensity to be prescribed, or, to identify unplanned changes in intensity that might indicate things such as fatigue.

Using this profile of impacts, practitioners can potentially track athletes and identify individual players whose load distribution pattern deviates from the mean profile (Figure 1. Histogram). A simple way of doing this is to monitor the steps/minute across the three intensity bands. It is beneficial to do this on an individual basis, given variability

between athletes.

The volume and magnitude of bilateral impacts provide an indication of the external training load and the intensity of these loads imposed upon the athletes. In order to be able to best prepare our athletes for training and competition, this requires a way of quantifying the types of loads, and discerning their volume and intensity to know if athletes are being adequately trained. Determining volume without also accounting for the intensity of the loads doesn't provide sufficient information for making informed decisions regarding training load prescriptions. For example, an athlete could have relatively the same number of total steps/min week to week, but if the intensity of these impacts shifts over time to greater intensities, the actual total loads imposed on the athlete is changing due to the magnitude of the impacts, and this may lead to things such as overuse injuries and tissue mal-adaptations (28). Gathering group data first is important so that you can establish a mean and a baseline from which to build the team's training program. From that group data, coaches and practitioners can monitor individual workload profiles, substantial increases in the counts of impacts at higher intensities, or increases/changes in total steps/minute. Changes in impacts on one limb may alter total cumulative loads leading to tissue damage, or may indicate things such as injury problems or decreased performance. Therefore, it is important to monitor each player in order to adjust for variances from the mean data. If there are major bilaterally differences in counts and intensities of impacts at the start of the season, practitioners can look to assess and determine if the athlete has decreased movement competency or strength, or other limitations, and devise appropriate training strategies to address them.

#### *Lower limb load and step counts*

Overall, there was no substantial team mean bilateral lower limb load/minute differences. In examining the results, the magnitude of variation between limbs is greater with load/minute than with steps/minute which is somewhat explained by the exponential weighting which indicates the importance of the magnitude of the load. The variability in bilateral loads was exacerbated by the daily load stimulus metric in comparison to counts of steps/minute. While there were no mean differences between limbs the CV suggests that there is a high amount of variation (6x greater for load/minute [CV=67.5%] than steps/minute [CV=10.1%]), therefore, further research looking at this load/minute metric is needed to determine the implications of this variation for players. For example, if a player displays no differences in total steps/minute bilaterally, but has substantial load/minute differences bilaterally, this

may be indicative of a greater contribution of the load coming from high intensity impacts, and would warrant further attention. An example of this could be something such as fatigue related changes in mechanics that may be responsible for these changes. Notably, several of the athletes displayed what look to be very large differences in load/minute between limbs in comparison to bilateral counts of steps/minute. The adapted tissue load metric accounts for the differential effect of larger impact intensities on tissue adaptation. In athletes 10 and 14 (Figure 7), the metric exacerbated loads such that much larger differences in load/minute between limbs existed than counts of steps/minute. For athletes 7 and 9, application of the metric resulted in greater loading on the limb with the lesser counts of steps/minute. Athletes may have relatively the same number of steps/minute week to week, but if the intensity of these steps shifts over time to much greater intensities, the actual loads imposed on the athletes are changing due to the magnitude of the impact forces, and this may lead to things such as overuse injuries and tissue mal-adaptations(24). By monitoring individual bilateral loads, these substantial increases in loading may be addressed more quickly in order to mitigate things such as injury problems or decreased performance. If there are major bilateral differences in loading at the start of the season, practitioners can look to determine if the athlete has decreased movement competency or strength, or other limitations, and devise appropriate training strategies to address the potentially problematic asymmetry. Given it is more reflective of tissue stress, the load/minute metric for quantifying external training loads may be beneficial in monitoring and prescribing training loads, monitoring and prescribing therapeutic (e.g. rehabilitation) loads, as well as quantifying changes in individual bilateral loads that may require further attention.

The individual variation in bilateral lower limb load/minute data for these athletes may be due to several factors. The primary factor contributing is likely related to differences in tasks (plays) and the different playing positions. Additionally, unlike a number of other sports, basketball is not played as a series of separate discrete tasks, instead they often flow from one into the next (e.g. such as landing from a jump to an immediate sidestepping manoeuvre to evade an opponent), making the training imposed loads more variable as a result of the tasks and their performance. This presents a challenge in terms of describing loads for a typical basketball training session. Other factors that may influence bilateral lower limb loads include fatigue and injury status, which may result in decreased ability of the muscles to attenuate impact loads. Changes in mechanical performance of various tasks can also influence the

magnitude of the impact loads, and on a larger level, the loads resulting from repeated bouts of these various tasks. An example of this is the influence of knee angle on impact attenuation across activities such as running and landing (55). Previous research has observed that increased knee flexion enhances the body's ability to attenuate these acceleration impacts occurring during running and landing. Having a method to monitor impact accelerations, may allow coaches and clinicians to determine if the changes they've elicited in an athlete's mechanical performance of these tasks have had a favourable effect on the body with respect to the impact loads. Practically, the load/minute data can be tracked graphically (daily and weekly) in order to evaluate things such as acute:chronic workload ratio and to allow coaches to visually observe a training load plan as experienced by each athlete as well as for the team. This allows for a systematic monitoring protocol for loading demands placed on the athletes during training.

The method and metric presented in this study is a simple, bilateral lower limb load monitoring protocol that can be used to quantify/evaluate training loads. Monitoring load throughout training may reveal periods during the training session where high loads occur, which may be indicative of things such as muscular fatigue or altered technical performance during acceleration/deceleration, jumping/landing, and changes in direction. This may be useful across both training sessions and competitions as it accounts for lower limb loads across dynamic tasks. The utility of this method is that it takes into consideration mechano-biological principles of musculoskeletal tissue adaptation(164), is specific to the lower limbs (where the greatest number of non-contact basketball injuries occur) (11, 12, 14, 189, 211-213)and allows for bilateral lower limb loads to be evaluated as injuries in the lower limbs tend to occur unilaterally. Accelerometers worn on the lower limb itself have been used in previous studies as a means of quantifying impact loads in the lower limbs. Research by Milgrom et al. (2003) looked at running used bone mounted accelerometers on the tibia to measure impact shock, representative of the strain imposed upon the musculoskeletal tissue (206). Furthermore, research looking at impact force attenuation using accelerometers on the tibia and the head found that there was a major reduction in impact forces measured between the two sites, indicating that impact accelerations measured superior to the area of interest may not be reflective of the loads imposed on the lower limbs (173). Additionally previous research has suggested a dose-response relationship exists between these impact loads and non-contact overuse injury problems. Moderate levels of loading can be beneficial to the musculoskeletal

tissue leading to increased structural integrity while excessive loading can lead to injuries (28). By monitoring these bilateral lower limb loads, it may be possible to lessen the risk of training load-based overuse problems (18).

### **Practical Applications**

The mean load profile identified in this research provides initial guidelines regarding the step volume and intensity distributions during trainings in professional men's basketball. This data may be useful in modeling the training load-injury relationships both individually and at the team level to maximize performance whilst minimizing injury risk. Practically, individual steps/minute profiles may be useful in determining load steps/minute and intensities for athletes so as not to prescribe loads that may substantially increase their risk of injury. Medical and coaching staff may then be able to use these individual load profiles and thresholds to make more informed decisions with respect to altering and managing an athlete's training loads.

Monitoring bilateral lower limb loading, using this novel DLS metric, may assist in the prescriptions of training protocols to better prepare athletes for the loads they will be exposed to. Further, this data provides coaches and practitioners with objective data to assess athletes' loading exposure without being influenced subjectively by an athlete with metrics such as session-RPE. While the findings of this research are useful in providing initial guidelines, practitioners should seek to use data specific to their team and athletes as load demands may vary between athletes and teams due to differences in position, playing style, and sport. In the future, modelling this data alongside internal workload measures as well as injuries may be beneficial for teams seeking to increase athlete physical preparedness while mitigating injury risk.

Although we were able to capture data from a team of elite level professional basketball players, our sample size is small. In the future, collecting this data over an entire season including during games, and using it to model the relationship between load and performance and load and injury may allow for this method to become even more informative in terms of decisions regarding training load prescriptions, rehabilitation, and recovery strategies.

### **Conclusions**

This research suggests that our simple method providing impact load data for athletes (steps/minute and intensities) and quantifying bilateral lower limb load

(load/minute) based on musculoskeletal tissue adaptation could be frequently monitored for potential use in both physical preparedness and injury risk models. This method allows practitioners to see step rate across load intensities, variability, and bilateral differences in step rate across intensities which may facilitate management of training loads for individuals and teams. Additionally, monitoring bilateral lower limb load via the daily load stimulus metric may be useful for support staff in identifying changes in load that may be associated with increased risk of lower limb injuries (particularly in instances in which steps/minute is insufficient to reflect these changes); managing increases in load so as to prevent spikes in acute loads that may be harmful; and, planning and modelling training loads and injuries to best prepare athletes whilst maintaining the lowest possible risk of lower limb injuries.



## CHAPTER 6: THE RELATIONSHIP BETWEEN TRAINING LOAD AND INJURY IN MEN'S PROFESSIONAL BASKETBALL PLAYERS

This chapter comprises the following paper accepted for publication in the International Journal of Sports Physiology and Performance:

Weiss, K., Allen, S., McGuigan<sup>1,3</sup>, M., & Whatman, C. (2017). The relationship between training load and injury in men's professional basketball players. *International Journal of Sports Physiology and Performance*.

### Abstract

**Purpose** To establish the relationship between the acute:chronic workload ratio and lower extremity overuse injuries in professional basketball players over the course of a competitive season.

**Methods** The acute:chronic workload ratio was determined by calculating the sum of the current week's session rate of perceived exertion (sRPE) training load (acute load) and dividing it by the average weekly training load over the previous four weeks (chronic load). All injuries were recorded weekly using a self-reported injury questionnaire (OSTRC Injury Questionnaire<sup>20</sup>) Workload ratios were modelled against injury data using a logistic regression model with unique intercepts for each player.

**Results** Substantially fewer team members were injured following workload ratios between 1-1.49 (36%) compared to very low ( $\leq 0.5$ ; 54%), low (0.5-0.99; 51%) or high ( $\geq 1.5$ ; 59%) workload ratios. The regression model provided unique workload-injury trends for each player, but all mean differences in likelihood of being injured between workload ratios were unclear.

**Conclusions** Maintaining workload ratios between 1-1.5 may be optimal for athlete preparation in professional basketball. An individualized approach to modelling and monitoring the training load-injury relationship, along with a symptom-based injury-surveillance method, should help coaches and performance staff with individualized training load planning and prescription, and with developing athlete-specific recovery and rehabilitation strategies.

## Introduction

The training-injury/performance relationship is important in professional sports as it can be extremely beneficial in determining the training stimulus required to maximize athletic performance while minimizing the risk of training load related non-contact injuries (43). The origins of this training dose-response relationship are based upon the statistical model proposed by Banister and colleagues (20) which estimated how an athlete would perform by examining the difference between the negative function (fatigue) and positive function (fitness) resulting from a specific workload stimulus. Currently, this model has evolved into the acute to chronic workload ratio, which evaluates the training load performed by an athlete with respect to the load they have been prepared for (21). Previous research across a number of sports using this method has found that both high and low workload ratios can result in increased injuries (21, 221, 222). Research in elite cricket fast bowling determined that when the acute:chronic workload ratio was  $\geq 1.5$ , the athletes' risk of injury was 2-4 times greater in the following 7 day period (21). Likewise, in rugby union, both low and high acute:chronic workloads were implicated in increased risk of injuries (222). Clear evidence of an acute:chronic workload ratio 'sweet spot' has been identified, where the likelihood of injury risk is lowest. Ratios that fall outside of this 'sweet spot' (both over and under-loading) display an increased likelihood of injury (222).

While this general workload/injury model is useful, there are several limitations in studies to date. Throughout previous studies, the injury definition used has been that of time-loss, which is commonly used for injury surveillance in team sports due to its simplicity in identification of injuries (21, 61, 62). However, this method is unlikely to reflect the true magnitude of the injury problem as many athletes will continue to train and compete despite the presence of an injury (64, 65). Thus, a more effective method for injury surveillance may be a recently developed self-reporting injury questionnaire, which takes into account the presence of symptoms and the impact of injury on an athlete's participation and performance in training and competition (68). Additionally, given the impact of individual characteristics on an athlete's response/symptoms as a result of training, it may be more beneficial to use an individualized approach for modelling this relationship, as opposed to prescribing loads based on the average team workload/injury model. For example, the same workload stimulus may have a different effect on two athletes due to variations in injury history, years of professional competition experience, and age. In some sports, especially those which have a small

number of athletes, individual models may be beneficial, especially at critical points in the season, where a starting athlete needs to compete despite the presence of injury symptoms.

Individualized workload/injury modelling-based training programs may be most important in sports such as basketball that are characterized by small squads, high training loads, back-to-back competitions, and a long season. Basketball, by virtue of its small squad size, and high training and match loads is extremely susceptible to performance decrements with time lost due to injury. Due to the lack of adequate recovery time, the risk of lower extremity injuries is inherently higher than other team sports with ankle and knee problems most common and knee problems having the greatest impact due to time loss from sport (11-13). Given that many of these non-contact injuries are attributed to excessive training loads, they may be largely preventable if the appropriate training loads are prescribed (43). Importantly the most successful teams in professional sports are those with the greatest number of players available to train and compete (223, 224). Currently, there is limited information regarding the workload/injury relationship in professional basketball. Thus, the purpose of this study was to investigate the relationship between the acute:chronic workload ratio and lower extremity, non-contact overuse injuries in professional basketball players over the course of a competitive season.

## **Methods**

### **Participants**

A professional men's basketball team ( $n = 13$ ) from the Australia New Zealand Basketball League (mean  $\pm$ SD; age,  $24.4 \pm 4.7$  years; height,  $195.0 \pm 7.6$  cm; body mass,  $96.3 \pm 11.6$  kg; competitive experience,  $5.9 \pm 3.6$  years) participated in this prospective study over one season (24-weeks, 36 games). All of the athletes were verbally informed of the purpose and procedures of this study during the team preseason intake and testing. The university ethics committee approved the research. Informed consent was obtained from all individual participants included in the study.

### **Methodology**

The session-rating of perceived exertion (sRPE) was used to estimate the internal workload for each of the athletes based on previous methods (202). Thirty minutes after the completion of each training session and game, the athletes rated their perception of the intensity using the modified Borg CR-10 RPE scale (202). The

training and game load arbitrary units (AU) were then quantified by multiplying each athlete's sRPE by training/game duration in minutes. This method has been used across multiple sports to quantify training loads as it has been observed to be highly correlated to blood lactate concentration as well as heart rate (47, 191). The acute:chronic workload ratio was determined by calculating the sum of the current week's sRPE training load (acute load) and dividing it by the average weekly training load over the previous four weeks (chronic load). The acute load represented the fatigue, while the chronic load was representative of the athlete's fitness or preparedness (21).

All injuries were determined using a self-reported injury questionnaire (68). Online survey software (Googledocs, California) was used to administer the OSTRC Injury Questionnaire to all athletes in the study once a week over the 24-week season. A group text reminder was sent by the team physiotherapist to the athletes every Sunday to ensure as many athletes as possible completed the questionnaire every week. The questionnaire consisted of four questions for each anatomical area of interest (ankle, knee and lower back) (68). If an athlete reported any symptoms on any of the four questions for each anatomical area, this was counted as an injury.

### **Statistical Analysis**

To investigate the existence of a specific workload-injury 'sweet spot' within professional basketball, we first evaluated the proportion of team members experiencing injury symptoms in the subsequent week at each of the following acute:chronic workload ratio ranges:  $<0.5$ ,  $0.5-0.99$ ,  $1.0-1.49$ ,  $\geq 1.5$ . Proportion ratios representing differences in likelihood of injury between ranges were assessed using a scale with thresholds of 1.11, 1.43, 2.0, 3.3, and 10 for small to extremely large increases, respectively, and their corresponding inverses for decreases (225). Qualitative mechanistic inferences about the true value of a difference were based on uncertainty in the magnitude of the ratio (expressed as 90% confidence limits): if the confidence interval overlapped values for a substantial increase and decrease, the ratio was deemed unclear; otherwise, the ratio was deemed clear and reported as the magnitude of the observed value (226).

Subsequent analysis to further explore the relationships between acute:chronic workload ratio and incidence of injury was conducted using the Glimmix procedure in SAS (Version 9.4, SAS Institute, Cary, NC, USA). Injury incidence was modelled as a

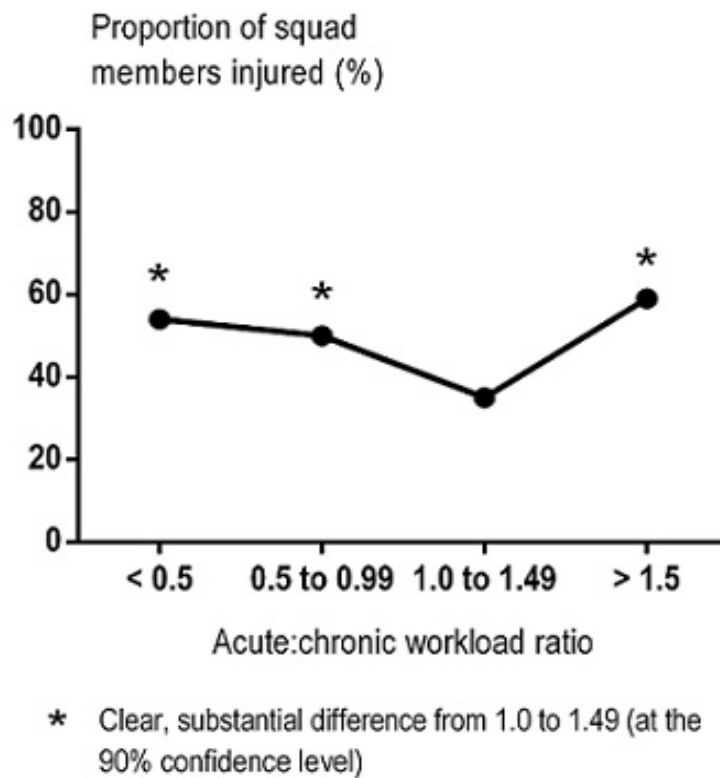
binary distribution (presence or absence of injury symptoms) with a logit link. The model included fixed effects to estimate a mean quadratic trend for acute:chronic workload ratio, and a random effect to estimate unique intercepts for each player's individual trend. Visual inspection of the data identified that several players did not complete a sufficient number of training weeks throughout the season both in the presence and in the absence of injury symptoms. Subsequently, we chose to perform this analysis with a sub-group of six players who had a minimum of three weeks of workload data under both conditions. Effects were derived from the model as odd ratios representing the mean differences in likelihood of experiencing an injury at different workload ratios. Magnitudes of effects were categorized according to the same thresholds used for the proportion ratios, and inferences about the true values of effects were again based on uncertainty in magnitude.

## Results

The proportion of team members experiencing injury symptoms in the subsequent week for each of four acute:chronic workload ratio ranges are presented in Figure 8. Proportions of injured squad members at workload ratios between 1.0 and 1.49 were substantially less than those observed at all other ratios by clear small-to-moderate amounts. Workload ratios  $\leq 0.5$ , between 0.5 and 0.99, and  $\geq 1.5$  resulted in 1.5, 1.4 and 1.7 times more injured players, respectively. Comparisons between all other workload ratio ranges were trivial-to-small in magnitude and unclear.

The mean quadratic relationship ( $\pm 90\%$  confidence limits) between acute:chronic workload ratio and likelihood of experiencing any injury symptoms in the subsequent week is displayed in Figure 9. All differences in likelihoods of subsequent injury between different workload ratios were unclear.

Figure 10 illustrates how mixed modelling of workload and injury data can be used to produce individual quadratic trends which represent each player's unique likelihood of experiencing injury symptoms in the subsequent week following particular acute:chronic workload ratios. Trends for these two athletes were chosen to exemplify individual differences in the workload-injury relationship for top basketball players.



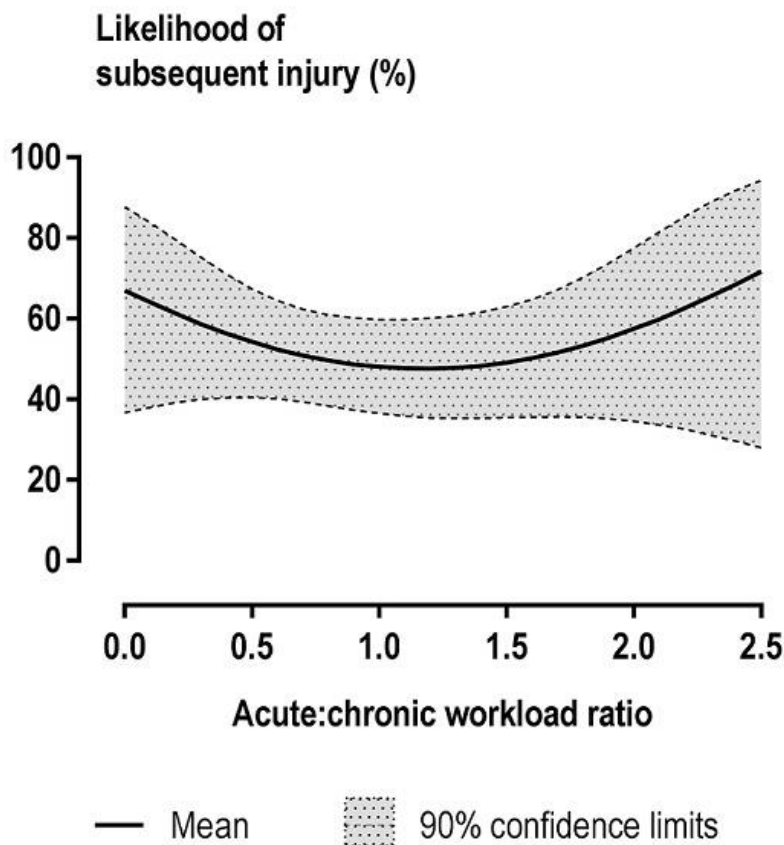
**Figure 6. Proportion of team members experiencing injury symptoms in the week following different acute:chronic workload ratio ranges.**

Uncertainties ( $\times/\div$  90% confidence limits) for pairwise comparisons of proportions between workload ratios of 1.0 to 1.49 and all other workload ratio ranges were  $\times/\div 0.30$ ,  $\times/\div 0.25$ , and  $\times/\div 0.50$ , for workload ratios of  $\leq 0.5$ , 0.5 to 0.99, and  $\geq 1.5$ , respectively.

## Discussion

By examining the relationship between workload and injury, coaches, performance and support staff may be able to make more informed decisions in prescribing training loads for optimizing physical performance while minimizing the risk of load-related lower extremity, overuse injuries in basketball.

In analyzing the impact of the workload ratio and injuries for the team as a whole, a clear trend emerged as to the overall impact of varying workload ratios on cost to the team in terms of injuries. Similar to previous studies in cricket (21), rugby league (222), and Australian football (227), we found an acute:chronic workload ratio 'sweet spot' (between 1.0 to 1.49), where a clear, substantial difference in percentage of injured athletes exists. However, unlike previous studies, the percentage of injured players at the 'sweet spot' remained relatively high (minimum 36%). This is a much higher percentage of injured players compared to values of approximately 3-6% in cricket, rugby league and Australian football (227) at similar acute:chronic workload ratios of 0.75-1.5. In a sport such as basketball, which has smaller team sizes, this relatively high percentage of injured athletes may have a much greater impact on team success due to both the total number of athletes available to compete as well as functional limitations for injured athletes that continue to compete through injury. Additionally, while this analysis gives an overall indication of the absolute injury risk for the team, it does not indicate individual responses to load. Even at the lowest risk point one third of the team was still injured, thus it may not be best to globally prescribe workloads to the team as a whole, as the risk of injuries is much greater in the current study than was presented among other sports. It should be noted that this greater total percentage of players injured in the current study may be due to differences in injury definition. However, we would argue that the injury definition and surveillance method used in this study provides a better indication of the magnitude of the injury problem in comparison to definitions used by other studies (68).

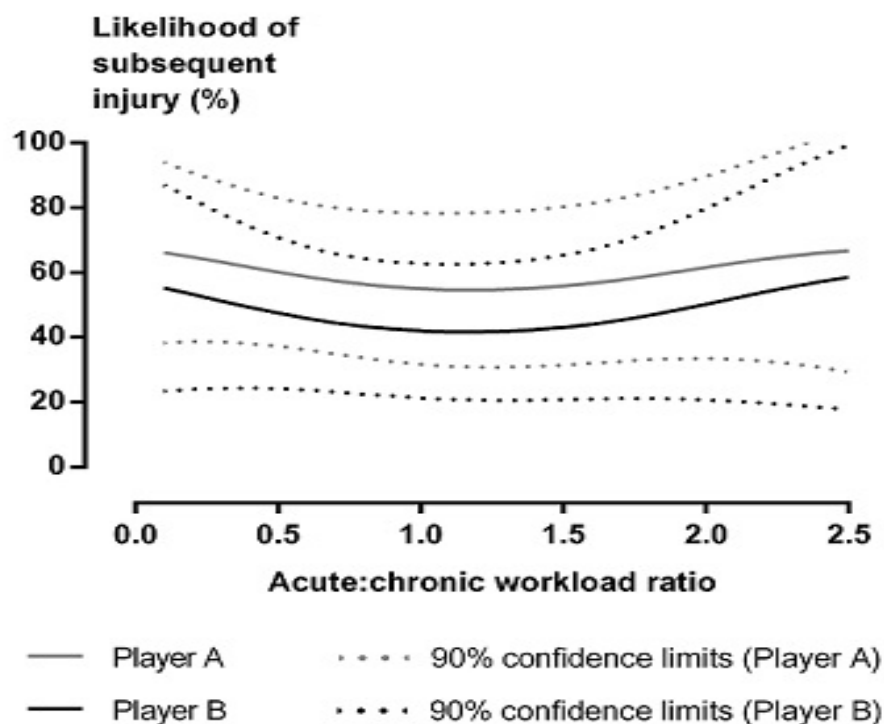


**Figure 7. The mean quadratic relationship ( $\pm 90\%$  confidence limits) between acute:chronic workload ratio and likelihood of experiencing any injury symptoms in the subsequent week for a group of six men's professional basketball players.**

Our regression model provided the same U-shaped relationship between workload and injury that has been observed across a number of other sports, whereby both high and low acute:chronic workload ratios are associated with increased injury risk (21, 228, 229). Although our analysis only involved six athletes - resulting in unclear differences in injury risk between all workload ratios - we were able to identify that the risk of injury at the workload 'sweet spot' was higher than has been reported in other sports. This is again high compared to other sports reported in previous studies where a risk of 5-10% was associated with the workload ratio sweet spot. There are several possible explanations for this difference. As already noted one aspect to consider is the injury surveillance method used. Based on our previous findings (26), the OSTRC questionnaire identified 4-6 times as many injury symptoms in comparison to a standard time-loss definition for identifying injuries used by the team physio. Assuming previous studies were using a more standard, time-loss injury definition (21, 222, 230), it may in fact be that the number of actual injuries documented doesn't truly



reflect the magnitude of injuries in each of the respective sports. Often times, with non-contact, overuse injuries, athletes will continue to train and compete, despite decreased functional performance, pain, and other injury related symptoms. This was why we chose to use the self-reporting questionnaire in order to truly capture the total number of injury problems relative to the workloads imposed on the athletes. We would again argue that given the presence of injury symptoms can lead to diminished performance, it is more important to examine the impact of training/playing loads on injury symptoms in order to determine what loads are best for reducing these symptoms. This is extremely valuable in basketball as a number of the athletes in the current study continued to train and compete despite reporting injury symptoms.



**Figure 8. Individual quadratic relationships ( $\pm 90\%$  confidence limits) between acute:chronic workload ratio and likelihood of experiencing any injury symptoms in the subsequent week for two men's professional basketball players.**

Though a 'sweet spot' in workload ratio existed at which the lowest percentage of team members was injured, an individualized approach might reduce this injury risk further. An individualized approach may allow for better injury management and prevention strategies. In previous research in rugby league, a training load model

devised to predict non-contact soft-tissue injuries found that athletes who exceeded their training load thresholds were 70 times more likely to develop an injury (171). By using an individualized model with each athlete (as per the example with two individual athletes, Figure 10), the relationship between the possible benefits of a specific training load stimulus versus its potential harm (i.e. increased likelihood of injury) can be assessed so that more appropriate evidence based decisions can be made. More specific training recommendations may increase the likelihood of success in cases where a player, who is not 100% fit, is needed for training and competition during playoffs in order to increase the chance of team success. This highlights both the importance and necessity for monitoring and prescribing training loads in professional sports such as basketball, which is characterized by high loads, back to back competitions, a long season, and a small squad.

Over the course of the study, three of the athletes had overuse injury problems across most of the season. Given these athletes were starters, they continued to compete despite being injured. Once a player has been injured and begins the rehabilitation process, it becomes difficult to elicit a large enough training stimulus to mimic the types of loads experienced during training and competitions. Due to this, these athletes may not have received an adequate training stimulus in order for them to be fully prepared to perform and compete. In general, when this is observed with athletes, returning to regular training and competition leads to changes in the workload ratio that can actually increase their risk of re-injury as well as their risk of developing new injuries. In the current study, the stimulus these athletes received during periods of recovery and rehabilitation may not have been enough to enhance physical preparedness for regular training and competition. It is possible that lower workloads between competitions decreased their preparedness to handle the physical demands of the games. It may also be that due to a small team, they had to compete in order to maintain team performance.

### **Practical Applications**

In the sports team setting, prescribing workloads so that they fall within the workload ratio 'sweet spot' range between 1.0-1.49 may be best early on when there is not enough data to show clear trends. Once more data is collected, individually prescribing training loads in conjunction with using a more realistic injury surveillance method should improve athletes' preparedness at the lowest possible risk of injury. This takes into account the individualized responses to load and the differences in

injury symptoms that may present themselves amongst different athletes on a team.

There are several limitations to this study that performance staff need to be mindful of when considering the applications of our findings. Due to the relatively small sample size and data from only a single season, some of the athletes did not display mean trends in order for clear model to be developed. Four athletes in the study had few or no injuries over the season, and therefore, no clear relationship emerged from their data. Additionally, three athletes in the study had previous injuries and illnesses which resulted in insufficient exposure to high workloads throughout the season, meaning trends for these players could not be properly assessed.

Furthermore, teams need to be aware that in order to be able to effectively create a training load-injury model for their athletes, data would need to be collected across multiple seasons. Teams should be mindful that self-reporting injuries could potentially result in under- or over-reporting of symptoms due to things such as fear of being excluded from team selection or an attempt to get some time off from participation. We don't think this occurred in the current study as the athletes viewed the questionnaire as additional information being collected for research and not connected to actual team decision making.

Future research that may inform further practical applications include looking at multiple teams over several seasons. In this type of sport, it is important that multi-centre collaboration be sought, along with standardization of reporting of injury, and documentation workloads in order for clearer models to be developed. It may also be of interest to develop and test a workload-injury prediction model to determine its efficacy in the sport. Based upon the way in which the modelling was performed for this study, the random effect in the model specifies that each of the athletes' trends should have different intercepts through the y-axis. This allows for each athlete to have the same sweet spot in terms of the workload ratio, but each also has their own likelihood of injury at each of the workload ratios. Future research should also consider collecting a greater amount of data using the same modelling protocol as the current study, adding in a random effect for different slopes for different athletes which would allow coaches and performance staff to identify individualized workload ratio 'sweet spots'.

## **Conclusions**

Maintaining workload ratios between 1.00-1.49 may be optimal for athlete preparation in professional basketball. An individualized approach to modelling and monitoring the training load-injury relationship, along with a symptom-based injury-surveillance method, should help coaches and performance staff with individualized training load planning and prescription, and with developing athlete-specific recovery and rehabilitation strategies. The use of an injury symptom based method for surveillance may be more practical and meaningful than traditional time-loss injury definitions, specifically when modelling the load-injury relationship.

## CHAPTER 7: THE RELATIONSHIP BETWEEN LOAD AND KNEE INJURY: A CASE STUDY IN PROFESSIONAL MEN'S BASKETBALL

This chapter comprises the following paper proposed for submission to the journal of Physical Therapy in Sport:

Weiss, K., Besier, T., & Whatman, C. (2017). The relationship between load and knee injury: A case study in professional men's basketball. *Physical Therapy in Sport* (in preparation).

### Abstract

**Purpose** This case study reports on a professional male basketball player who developed a left knee injury during the competitive season. The report presents a retrospective review of knee moments measured pre-season; lower limb load collected in training using wearable accelerometers; and, weekly scores from a self-reported questionnaire designed to detect overuse knee problems.

**Methods** The data collection involved three separate protocols: (i) pre-season 3D motion capture assessment of peak knee moments during basketball specific tasks, (ii) in-training inertial accelerometer based bilateral lower limb load monitoring protocol, and (iii) weekly self-reported knee overuse symptoms completed for the entire season.

**Results** Lower limb loads in training were greater on the right limb than the left. The steps/minute were higher on the right at high impact intensities (right: 6.9 steps/minute; left: 5.2 steps/minute) but not at low impact intensities (right: 9.4 steps/minute; left: 12.3 steps/minute). Peak knee moments were higher on the left than the right in the frontal (mean difference: ~10 Nm) and transverse (mean difference: ~6 Nm) planes during some tasks and the self-report questionnaire showed a spike in left knee symptoms immediately prior to the injury.

**Conclusions** This case study provides preliminary data highlighting a new perspective on knee injury risk assessment, monitoring, and management. By looking at the combined metrics, practitioners may be able to better address the potential mechanisms influencing the associated increased risk of knee injury.

## Introduction

Injury rates in professional basketball are among the highest of all non-contact team sports (8, 9). The majority of these injuries occur in the lower extremities, with the most frequently reported lower extremity injuries being overuse knee injuries, specifically anterior knee pain (AKP) and cartilage lesions (12-14). The highest number of games and trainings missed have been attributed especially to knee injuries, making them of particular interest and focus in terms of understanding the underlying causes, developing preventative measures, and mitigating risk in basketball (14, 15, 186).

In general, research in sports injuries has focused on measuring joint moments as they have been thought to be causative factors in the development of these knee injuries (123, 231). Traditionally, these joint moments (loads) have been evaluated in a laboratory using 3D motion capture and force plates (92, 232). While much focus has been on the transverse and frontal plane moments, measurement of these loads outside of the lab has been neglected. With traditional laboratory 3D motion capture, athletes often constrain their movements, and it is difficult to replicate the environmental conditions they encounter as part of their sport, thus making the resulting data less applicable in actual sporting conditions (173, 233). More recently, the advent of wearable technology has introduced the use of accelerometers as a means of monitoring surrogate measures of mechanical loads (206). Several studies have quantified mechanical load by attaching accelerometers on the tibia to measure impact shock, representative of the strain imposed on the lower extremity musculoskeletal tissue (173, 206). Use of a wearable measurement system allows monitoring of lower extremity loads on the court during real-time sporting conditions. However, the metrics obtained are surrogate measures of load, which may decrease the relevance of the measures (206).

Though not a specific load monitoring tool, the simple monitoring of symptoms may be another useful method for monitoring load as symptoms result from loads that increase stress and strain on the musculoskeletal tissue (68, 234). A recently developed, self-reported questionnaire has been used effectively across a number of sports to evaluate the impact of overuse symptoms (63, 68). The questionnaire focuses specifically on knee joint symptoms and their impact on training and competition participation and has been reported to identify more problems than a traditional time loss injury definition (26, 63). It is simple and effective in monitoring overuse symptoms, but may not be able to identify specific factors related to injury risk until the presence of symptoms already exist. In order to better understand the potential mechanical risk factors that contribute to overuse knee injuries, it may be beneficial to consider the

relationship between laboratory knee kinetics, accelerometer tibial impacts in training and self-report knee symptoms.

This case study reports on a professional male basketball player who developed a knee injury during the competitive season. The report presents a retrospective review of knee moments measured pre-season using: traditional 3D motion capture; surrogate measures of lower extremity load collected in season using wearable accelerometers; and, weekly scores from a self-reported questionnaire designed to detect overuse knee problems.

## **Case Study**

A 29 year old male professional basketball point guard (weight = 94.1 kg, height = 191 cm), sustained a patellofemoral/meniscal injury to the left knee with a cartilage lesion and some effusion during the 2015-2016 season. The injury was first diagnosed by the team physiotherapist and then verified using magnetic resonance imaging by an orthopaedic surgeon.

The athlete's previous two-year lower limb injury history included development of a bone spur on the heel of the right foot two years previously.

## **Methods**

The data collection involved three separate protocols: (i) the pre-season 3D motion capture laboratory testing protocol, (ii) the in-training inertial accelerometer based bilateral lower limb load monitoring protocol, and (iii) the weekly self-reported knee overuse symptom questionnaire (completed for the entire season).

### **Laboratory testing protocol**

The pre-season movement assessment included 3D motion analysis with force in all three planes, for assessment of knee kinematics and kinetics. Testing took place one week prior to the start of pre-season team training, and lasted approximately 60 minutes at which time the player was injury free. A self-selected 10-minute warm-up along with practice of each of the dynamic tasks were performed until the athlete felt comfortable with the various tasks in the laboratory.

Three-dimensional motion analysis consisted of eight of each of the following common basketball-specific tasks, including: sidestepping right and left at a self-selected run up speed at approximately 2.5 m at approximately 45 degrees; drop jumping (rebounding) off of a 35cm box; running at a self-selected pace; and, jump

shot maneuvers.

Retroreflective markers (10 mm) were attached bilaterally to anatomical landmarks following the lower limb marker set reported by Mason-Mackay et al. (235). After completing the static calibration, femoral condyle and malleoli markers were removed. To determine functional joint centres the dynamic calibration of the hip joint involved the athlete moving first the right then the left leg through a combination of flexion, abduction, adduction and extension (236); and, the knee joint centre dynamic calibration involved three squat movements (236).

A 9-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with two Bertec (BERTEC Corp., Worthington, OH, USA) force platforms were used for collecting the knee kinematic (200 Hz) and kinetic (1000 Hz) data. The functional joint positions were calculated using a custom-built, MATLAB constrained optimization program (*Optimization Toolbox*, Mathworks Inc., Natick, MA, USA) (236). The peak joint angles and moments were calculated via inverse dynamics using OpenSim software (*sim.tk*).

### **Statistical analysis protocol**

We calculated means and standard deviations for peak knee moments in the sagittal, frontal and transverse planes. Paired t-tests were performed using a published spreadsheet (Hopkins, 2003) to investigate the mean difference between limbs. We used non-clinical magnitude-based inferences to assess these differences (Hopkins, Marshall, Batterham, and Hanin, 2009), whereby the smallest important difference was the average of the right and left standard deviations multiplied by 0.2. Thresholds for moderate, large and very large differences were (0.6, 1.2, and 2.0) of this average. Uncertainty in mean differences was expressed as 90% confidence limits and as likelihoods that the true value of the effect represents a substantial difference between limbs (Batterham & Hopkins, 2006). Where the effect had a >5% probability of being substantially positive and a >5% probability of being substantially negative the inference was stated as ‘unclear’ (220).

### **Wearable accelerometer protocol**

Bilateral inertial accelerometers (IMeasureU, Auckland, New Zealand) were worn on the antero-medial distal 1/3 of the tibia between the medial malleolus and tibial plateau during a typical basketball training session. The accelerometers were firmly attached using double sided tape to secure the accelerometer to the skin and a layer of bandage (Amtech cohesive bandage 75mm) was used to minimize movement



that could lead to soft-tissue artefacts. The accelerometers measured tibial shock, or impact accelerations, which served as a surrogate measure of lower extremity load. The tri-axial accelerometer data was data logged and sampled at 1000 Hz. Following previously reported methodology, the accelerometer data resultant impact accelerations were binned in 2g increments (2-16g) and the total counts of steps/min were determined bilaterally for low (2-4g) moderate (4-10g) and high (10-14+g) intensities. Lastly, lower limb load was calculated using the daily load stimulus equation shown below. Left and right lower limb loads and the loading rate ratio between sides (right versus left) were then calculated (this was completed for both the steps/min and the lower limb load).

$$\text{Daily Load Stimulus (DLS)} = [\Sigma (\sigma)^m (n)]$$

The symbols represent the following:

- $\sigma$  the effective stress (or strain) per loading condition (peak impact accelerations)
- $n$  the number of loading cycles per loading condition (counts of impacts at each magnitude)
- $m$  the weighting factor

### **Self-reported questionnaire protocol**

Online survey software (Googledocs) was used to distribute the OSTRC Overuse Injury Questionnaire (68) to the athlete each week for 24 weeks. A reminder was sent out each Monday morning to complete the questionnaire. The questionnaire consisted of four questions on the knees as they were the area of interest (68). Every time the athlete responded to the weekly questionnaire, a severity score was calculated based on responses to the four questions (68).

### **Results**

Overall lower limb loads in training were greater on the right limb (165229 load [unitless measurement]/min) than the left (122789 load [unitless measurement]/min). The steps/min were also higher on the right at high impact intensities but not at low impact intensities (Table 5).

Intensity	Limb	Steps/minute
Low	<b>Right</b>	9.4
Low	<b>Left</b>	12.3
Moderate	<b>Right</b>	30.1
Moderate	<b>Left</b>	30.3
High	<b>Right</b>	6.9
High	<b>Left</b>	5.2

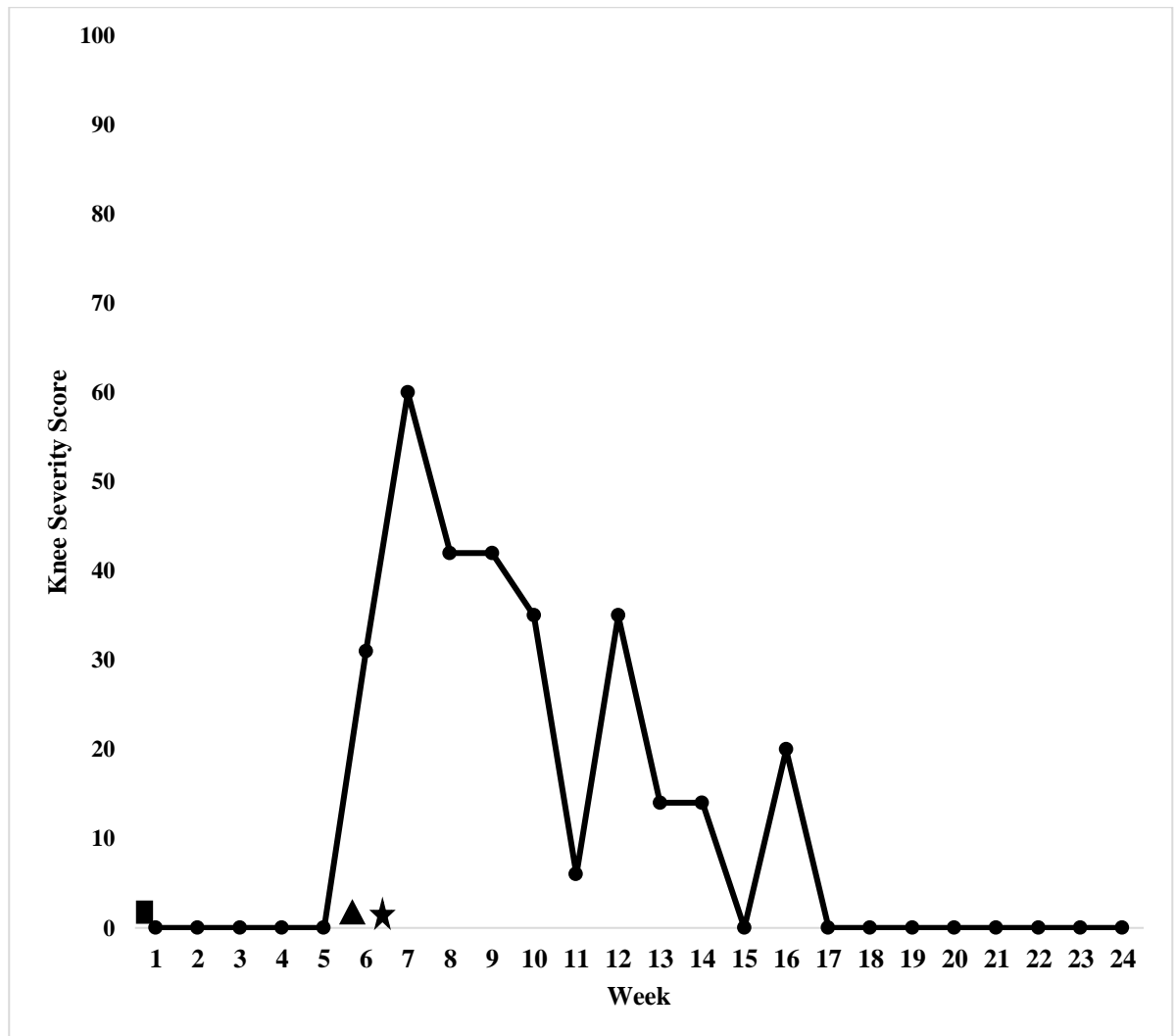
**Table 5. The above table shows steps/minute at each intensity.**

Laboratory motion analysis revealed generally higher peak left knee frontal (mean difference: 9.7-9.9 Nm) and transverse plane moments (mean difference: 1.6-6.4 Nm) (Table 6). The frontal plane moment during the sidestep was greater on the left than right and the transverse plane moment was also higher on the left during the jump shot and rebound (Table 6). The transverse plane moment during running was higher on the right than left. The mean difference in frontal plane moments during the sidestep had a moderate effect with the left likely less than the left, and for the transverse plane the effects were very large for the jump shot (left almost certainly greater than the right), rebound (the left almost certainly greater than the right), and run (the right almost certainly less than the right) (Table 6).

	Peak Knee Moments (Nm) $\pm$ SD		Mean Difference	Effect Size	Qualitative Inference
	Right	Left	(Right-Left) $\pm$ 90%CI		
<b>Jump Shot</b>					
Sagittal	35.9 $\pm$ 5.3	38.4 $\pm$ 6.2	-2.5 $\pm$ 6.1	Moderate	unclear
Frontal	19.0 $\pm$ 10.1	28.7 $\pm$ 10.2	-9.7 $\pm$ 12.2	Moderate	unclear
Transverse	4.7 $\pm$ 1.6	10.3 $\pm$ 2.5	-5.6 $\pm$ 1.6	Very Large	almost certainly L>R
<b>Rebound</b>					
Sagittal	39.3 $\pm$ 7.9	45.4 $\pm$ 11.5	-6.1 $\pm$ 9.2	Moderate	unclear
Frontal	33.4 $\pm$ 2.2	32.9 $\pm$ 7.3	0.5 $\pm$ 8.5	Large	unclear
Transverse	6.7 $\pm$ 1.9	13.2 $\pm$ 3.5	-6.4 $\pm$ 2.8	Very Large	almost certainly L>R
<b>Run</b>					
Sagittal	16.0 $\pm$ 3.1	15.3 $\pm$ 3.2	0.7 $\pm$ 3.8	Moderate	unclear
Frontal	17.3 $\pm$ 9.9	14.8 $\pm$ 11.4	2.5 $\pm$ 20.4	Large	unclear
Transverse	7.4 $\pm$ 1.6	2.1 $\pm$ 0.5	5.3 $\pm$ 1.6	Very Large	almost certainly R>L
<b>Sidestep</b>					
Sagittal	18.9 $\pm$ 2.0	15.6 $\pm$ 2.7	3.4 $\pm$ 5.4	Very Large	unclear
Frontal	18.2 $\pm$ 8.3	28.1 $\pm$ 5.7	-9.9 $\pm$ 8.2	Moderate	likely, probable L>R
Transverse	10.7 $\pm$ 4.6	9.8 $\pm$ 7.9	-1.6 $\pm$ 19.2	Very Large	unclear

**Table 6. Peak Knee moments (Nm) during a jump shot, rebound, run, and sidestep manourvre. The mean peak knee moments are displayed for the right and left limb, along with the mean difference (right-left)  $\pm$  90% CI (confidence interval). Effect size thresholds for moderate, large and very large differences were (0.6, 1.2, and 2.0). Uncertainty in mean differences was expressed as 90% confidence limits and as likelihoods that the true value of the effect represents a substantial difference (ES > 0.2) between limbs. Where the effect had a >5% probability of being substantially positive and a >5% chance of being substantially negative of being unclear.**

The self-report questionnaire showed a spike in left knee symptoms immediately prior to the injury (Figure 11).



**Figure 11. The Oslo knee overuse injury questionnaire symptom weekly severity scores. The square indicates the laboratory motion analysis data collection date, the triangle indicates the wearable accelerometer data collection date, and the star indicates the date of the left knee injury.**

## Discussion

This case study retrospectively reviewed several different metrics for determining lower limb loads in an athlete that developed a knee injury. These metrics included: knee moments measured pre-season using traditional 3D motion capture; surrogate measures of lower extremity load collected in season (pre-injury) using wearable accelerometers; and weekly scores (symptoms) from a self-reported questionnaire designed to detect overuse knee problems during the competitive season. While each of the methodologies used have previously been examined in isolation, we suggest that examining the results

of the combined metrics may be useful in managing injury risk. Combining data from each of the three separate methods potentially provides greater detail so as to allow practitioners to better address specific mechanisms that may be contributing to increased risk of injury.

The results of the accelerometer-based surrogate measure of knee joint loads indicated greater lower limb loads on the right side in comparison to the left. However, the steps/min at low intensities was greater on the left, but at high intensities, was greater on the right. This may be due to an attempt by the athlete to offload the left side as pre-injury symptoms developed prior to the onset of injury. Given that the body experienced greater loading on the right at higher intensities, it may be that this side was better prepared to sustain greater loading, and that perhaps the total load tolerance on the left side at higher intensities was lower. The accelerometer provided information on cumulative load exposure, however it was unable to evaluate specific knee moments. Additionally, the cumulative loads, as well as the distribution of the counts of impacts across intensities need to be considered alongside the presence or otherwise of knee symptoms. Without this additional information, differences in cumulative loads are difficult to interpret in terms of risk of injury.

Interpretation of the accelerometer based load data can potentially be improved by considering the knee moments recorded in the laboratory. Based on the 3D motion capture data, greater transverse plane knee moments were observed on the left side during the jump shot and rebound tasks. Additionally, while statistically unclear, during sidestepping, the athlete also experienced, on average 10 Nm (moderate difference, unclear) more frontal plane (valgus) loading on the left side. Across a variety of sports, the most common kinetics associated with knee injuries include excessive transverse and frontal plane loads (90). This is because these moments place additional load on the patellofemoral and tibiofemoral joints, increasing the associated risk of knee injuries (90). Thus the laboratory data suggests potential concern regarding increased left knee load in the athlete, however the picture is far from clear. In conjunction with the greater loading on the left at low intensities, experiencing greater peak moments on the left side may have led to decreased structural integrity of the tissue, and increased the likelihood of sustaining an injury from a sudden increase in high impact load. While the greater transverse plane moments on the left side during the jump shot and rebound raise some concern, more information is provided by the other measures to confirm the likely increased risk. Though greater knee moments can indicate increased risk, it is also a

possibility that the athlete's musculoskeletal tissue may be adapted to attenuate these loads. Yet, when considered alongside the accelerometer data, it presents a different picture. With the left side potentially having decreased load tolerance capacity, these types of moments may have led to the greater risk of injury. By combining knowledge of the increased left knee moments with the greater rate of loading on the left side at low intensities recorded in training may help explain the subsequent injury to the left knee.

Lastly, just prior to the manifestation of the injury, the athlete reported knee overuse symptoms after being asymptomatic the previous two weeks. While this doesn't provide direct information regarding knee loads or cumulative load exposure, the presence of knee overuse symptoms may indicate decreased load tolerance both in terms of peak loads and cumulative loads. The questionnaire specifically addresses knee symptoms (referring to pain, ache, stiffness, swelling, instability/giving way, locking or other complaints) related to difficulties participating in normal training and competition, needing to reduce training volume, reduced performance, and pain (63). Both frontal and transverse knee moments and excessive lower limb loads place stress and strain on the tissue that may result in changes in knee score addressed by the questionnaire (24, 28, 40). Therefore, although the questionnaire doesn't directly identify causation, the presence of reported knee problems provides insight regarding the musculoskeletal tissue's response to its current local mechanical load environment. Based on previous research by Dye (1996), the ability of the knee joint to tolerate peak loads decreases over time. Repetitive loading, can lead to decreased structural integrity, increasing the risk of injury and the presence of overuse symptoms. Whereas the types of loads differed between sides, the total counts of steps/min between sides was relatively the same. Despite these loads being smaller on the left, the left may not be prepared to sustain larger peak loads, so even repetitive loading and lower intensities may have led to decreased structural integrity and ability to tolerate larger peak loads over time (especially in comparison to peak load tolerance in the right limb). The athlete's self-reported overuse symptoms may have been a possible indication of decreased load tolerance. Thus, by considering the laboratory knee load data, the cumulative accelerometer load data, and the overuse symptom data together, we get a clearer indication of the loading environment and the presence of symptoms that may have led to the greater associated risk of knee injury on the left side. When this knee score information is considered alongside the accelerometer loads and knee moment data, it confirms the need for intervention in order to reduce the risk of injury.

This combination of methods provides a new perspective for knee injury risk assessment, monitoring, and management. Paramount in the effectiveness of this approach is that it takes in to consideration how each of these metrics are influenced by each other as well as monitoring the presence of symptoms related to the impact of the loads on the tissue. Although they provide some information, neither knee moments nor cumulative loads alone provided a clear indication of increased injury risk. However, by combining the two and adding self-reported symptoms, we get a clearer picture of the increased risk of subsequent knee injury. Both knee moments and loading (cumulative and steps/min) are potentially modifiable factors which can be addressed through training interventions designed to correct mechanics (e.g. frontal and transverse in this case) and periodise training loads. The success or effectiveness of these interventions can be monitored using the OSTRC questionnaire as well as the inertial accelerometers. Through continuous and frequent monitoring using these strategies, a more individualised approach can be applied in prescribing training loads and exercises aimed at reducing injury risk.

## CHAPTER 8: DISCUSSION AND CONCLUSION

Basketball has been identified as having the highest incidence of injuries across non-contact sports (8, 9). Overuse injuries are considered the primary injury type in sports such as basketball (10), however, their magnitude and severity is poorly understood(66, 67). Many athletes will continue to participate in training and matches despite experiencing pain and decreased function due to an overuse injury (63, 64). As a result, the standard time-loss definition of injury used in many studies may largely underestimate the number of overuse injuries. In order to be able to effectively prevent these injuries, the link between training loads and injury problems must first be established. While this relationship has been monitored across a number of sports, it has yet to be explored in basketball. Additionally, the methods and metrics for quantifying training loads is sparse in the basketball training load and injury literature. With a majority of the basketball injury problems originating in the lower limbs (12-14), the previously proposed methods of using wearable technology mounted on the upper body (50) may not provide the most appropriate external load data for understanding lower limb injury risk.

Given the limitations identified in the literature, the questions addressed in this thesis sought to quantify the relationship between training loads and injuries (specifically overuse lower limb injuries) in male professional basketball players. In order to effectively investigate this question, three main themes were explored. The first thematic section established the biomechanical/load factors associated with lower limb injury risk and cumulative/adaptive tissue load in sport. First, a systematic review of the research pertaining to biomechanics associated with increased risk of knee injuries in sports (Chapter 2) was presented to outline the relationship between load and knee injuries in sports. Then, a narrative review identified the importance of cumulative lower limb loads on injuries using an adapted tissue load equation, which was presented as a novel approach to quantifying the load-injury relationship (Chapter 3). The second thematic section focused on the quantification of overuse injury and load in professional basketball through the use of wearable technology and a recently developed overuse injury questionnaire. The magnitude and prevalence of common overuse injuries (ankle, knee, low back) in professional basketball was determined using a self-reporting overuse injury questionnaire (Chapter 4). After establishing the importance of monitoring load and the prevalence of overuse injuries common in basketball, the thesis proposed a method for quantifying lower limb loading



(steps/minute and load/min). This was performed first by monitoring the counts of impacts at low, moderate, and high intensities using wearable accelerometers followed by using the proposed lower limb impact load monitoring methodology along with an adapted tissue load metric proposed in Chapter 3 to quantify external, or mechanical, bilateral lower limb loads (Chapter 5). Lastly, the third thematic section investigated the relationship between load and injury in professional basketball. To accomplish this, the thesis then quantified internal, physiological loads using the session-RPE (session-rate of perceived exertion) method and then examined their relationship to injury (Chapter 6) in professional basketball. Finally, several methods for quantifying lower limb loads (overuse injury questionnaire, wearable accelerometers, and 3D motion capture) were evaluated together as part of a knee-injury case study (Chapter 7). The following discussion summarises the results and inferences relative to each of these themes.

### **Theme 1. Biomechanical factors associated with lower limb injury risk and cumulative load in sport.**

From the first thematic section of the thesis, biomechanics associated with knee injury risk were established, along with a proposed method for quantifying cumulative lower limb loads associated with injury. The purpose behind the systematic review (Chapter 2) was to evaluate biomechanics associated with two common knee injuries (PFPS and ACL) in sports involving landing, change in direction, or rapid deceleration across the three time points frequently reported in the literature: pre-injury, at the time of injury, and following injury. Based on the findings from the review, both ACL injuries and PFPS are associated with similar biomechanics in the frontal and sagittal planes for the knee and hip across all time points (pre-, at, and following injury). The reduced ability of the lower extremity to dissipate forces during landing and sidestepping tasks appears to be an underlying internal factor related to these injuries. The combination of increased frontal plane loading, particularly at the knee, in conjunction with decreased mechanical control of the hip, increases the stress acting on the tissues and structures of the knee. Practically, development of injury prevention programmes should focus on correcting these mechanics during high risk manoeuvres as this may help decrease the prevalence of these injuries. Programmes should focus on neuromuscular training alongside correcting mechanics during these high-risk manoeuvres. By looking at different biomechanical research approaches, it was possible to assess not only the mechanism of injury, but also to look for commonalities

in biomechanics between injured and un-injured participants pre-injury, at the time of injury, and following injury, to better understand potential causes of PFPS and ACL injury. This led to the conclusion that cumulative lower limb loading may be worth investigating with respect to knee injury risk.

In Chapter 3, the influence of cumulative lower limb mechanical load on musculoskeletal tissue homeostasis and injury risk was described, a cumulative load metric [Daily load stimulus] was introduced, and appropriate methods to quantify cumulative lower limb load in the field were examined. It was concluded that having a field-based, simple method to quantify and monitor mechanical loads could be an important step in the prevention and management of chronic musculoskeletal injury. Furthermore, concepts of musculoskeletal mechanobiology should be integrated within the load measurement system to account for tissue adaptation (127). Musculoskeletal tissue is influenced by mechanical loads, such that the loads can either be positive, leading to enhanced structural integrity; or, they can be harmful, resulting in injuries or disease (28, 127). Many tissue injuries are due to cumulative loading and fatigue-damage, which can be assessed using a stress-related criteria that accounts for magnitude of load and total loading cycles. To effectively measure and monitor lower limb cumulative loads in sport, mechanobiology principles should be integrated with load measurement as part of the surrogate metric. From a practical standpoint, wearable accelerometry could provide a convenient surrogate measure of lower limb loads. Wearable accelerometers in combination with the concept of the daily load stimulus, may provide insight into fatigue-related injuries that can be measured in the field.

## **Theme 2. Quantifying overuse injury and load in professional basketball.**

Several methods were used in this thematic section to quantify overuse injury and load in professional basketball. The first study in this section sought to determine the magnitude of the overuse injury problem in professional men's basketball (Chapter 4). This study (Chapter 4) used the OSTRC overuse injury questionnaire to record overuse injuries over a single season for a men's professional basketball team. A total of 183 overuse conditions were identified by the questionnaire, whereas only 28 overuse conditions were identified by the physiotherapist using the standard (time-loss) definition. The team's average weekly prevalence of all overuse conditions was 63% (95%CI:60-66) with the highest prevalence of injury affecting the lower back (25.9%

[95%CI:19.7-32.1]). The overuse injury rate per 1000 hrs of athlete exposure was 6.4. The OSTRC overuse injury questionnaire captured many more overuse injuries in basketball than standard reporting methods. The prevalence of lower back injuries was higher than previously reported in basketball (12-14). This additional method of overuse injury surveillance may aid earlier intervention, potentially mitigating the impact and severity of the overuse conditions. This may be a more practical surveillance strategy in the team sport setting as it is more likely to reflect the current injury status and performance capacity of the team, which is important especially during key time points such as playoffs, where athletes may need to compete despite the presence of injury problems. The data provided using the questionnaire may also help in making more informed decisions such as whether an athlete will compete during these crucial points in the season. It may also provide a means of greater communication between the athletes and medical staff, which may help in decreasing the number of overuse injuries.

Once the overuse injury problem had been established, the next area of focus was on how to quantify external load and specifically lower limb loads, followed by internal loads (session-RPE). In Chapter 5, wearable accelerometers were used during professional basketball trainings to: (1) quantify bilateral lower limb steps/minute, step intensity, and lower limb load/minute [using an adapted tissue load metric (Daily load stimulus)]; (2) investigate limb asymmetry in the context of steps/minute and load/minute; and, (3) examine differences in bilateral lower limb loads using counts of impacts versus the adapted tissue load metric [Daily load stimulus]. The greatest steps/min occurred at moderate intensities with the team mean data appearing to have similar bilateral loading rates across intensities. There appeared to be differences in steps/min bilaterally between individuals and for individuals between the three intensities. This data may be most useful in modeling the training load-injury relationships both individually and at the team level to maximize performance whilst minimizing injury risk. Practically, individual load profiles may be useful in determining load steps/min and intensities for athletes so as not to prescribe loads that may substantially increase their risk of injury. Medical and coaching staff may then be able to use these individual load profiles to make more informed decisions with respect to altering and managing an athlete's training loads (18).

As discussed in Chapter 3, the daily load stimulus is a load metric that takes into account the magnitude and frequency of loads, as well as a weighting factor. This

suggests that different load magnitudes will impact the musculoskeletal tissue differently (127). For the purposes of this research, it served as a good model for evaluating the impact of basketball training on the musculoskeletal tissue in the lower limbs (164). Further, it potentially allows for a better indication of load volume than counts of impacts alone. It was found that the team mean bilateral lower limb load/min appeared to be similar between limbs, whereas there appeared to be variability in the bilateral lower limb load/min data between individuals and between limbs when considering individual athletes. This variability in bilateral loads was exacerbated by the daily load stimulus metric in comparison to the counts of impacts. This research suggests that the simple method of quantifying bilateral lower limb load based on musculoskeletal tissue adaptation (rather than a count of tasks) should be a viable option for teams across a variety of sports in terms of daily athlete training load monitoring. Monitoring bilateral lower limb load via the daily load stimulus metric may be useful for support staff in identifying changes in load that may be associated with increased risk of lower limb injuries; managing increases in load so as to prevent spikes in acute loads that may be harmful; and, planning and modelling training loads and injuries to best prepare athletes whilst maintaining the lowest possible risk of lower limb injuries.

### **Theme 3. The relationship between load and injury in professional basketball.**

The final thematic section of the thesis explored the relationship between load and injury. In Chapter 6, the session-RPE method was used to monitor internal training loads, and the relationship between training loads and overuse injuries based on the data obtained from Chapter 4 were modeled. In the training load-injury literature, overuse injuries have been linked to workloads, which are considered modifiable and controllable (18). While numerous studies have used a variety of overuse injury surveillance methods, it was felt to be a more valid method for monitoring overuse injuries (e.g. the OSTRC questionnaire) should be employed in order to more effectively assess the relationship between workload and injury. The findings determined that maintaining acute:chronic workload ratios between 1-1.5 may be optimal for athlete preparation in professional basketball. An individualized approach to modelling and monitoring the training load-injury relationship, along with a symptom-based injury-surveillance method, should help coaches and performance staff with individualized training load planning and prescription, and with developing

athlete-specific recovery and rehabilitation strategies. In the team sport setting, prescribing workloads so that they fall within the workload ratio range between 1-1.5 may be best early on when there is not enough data to show clear trends. Once more data has been collected, individually prescribing training loads in conjunction with using a more realistic injury surveillance method should improve athletes' preparedness at the lowest possible risk of injury. This takes into account the individualized responses to load and the differences in injury symptoms that may present themselves amongst different athletes on a team.

The final retrospectively investigated several different metrics for determining lower limb loads and their relationship to a knee injury case that occurred during the season (Chapter 7). These metrics included: knee moments measured pre-season using traditional 3D motion capture; surrogate measures of lower extremity load collected in season (pre-injury) using wearable accelerometers; and weekly scores (symptoms) from a self-reported questionnaire designed to detect overuse knee problems during the competitive season. While each of the methodologies used have been examined previously in isolation in the literature, the findings suggest that examining the results of the combined metrics may provide a more informative picture of the increased risk in potential injury. Although overall, the uninjured limb experienced greater training loads and steps/min at higher impact intensities, greater lower limb loads and steps/min were observed at lower intensities in the injured limb. This in conjunction with higher peak knee frontal and transverse plane moments that were present during the laboratory motion analysis in the injured limb, adds a bit more detail as to why there may have been an increased associated risk of injury. Finally, prior to the manifestation of the injury, the self-reported questionnaire showed a spike in symptoms immediately prior to the injury. Thus, it is the amalgamation of the data from each of the three separate methods that provides greater detail so as to allow practitioners to better address specific mechanisms that may be contributing to the increased injury risk. It is important to note that while each of these metrics suggested an associated increased risk of injury, on their own, each metric provided only some information relative to the risk of injury. It is important to note that each of these metrics is influenced by the other. Knee moments and loading (load/minute and steps/minute) can potentially be modified through training interventions developed to correct mechanics and periodise training loads. These strategies can then be assessed using the OSTRC questionnaire and wearable accelerometers. The use of multiple load monitoring methods such as

those presented in the thesis may be best in order to prevent the risk of lower limb injuries. The combination of the metrics together allows for a better understanding of what the athlete may be experiencing and possible interventions that are most appropriate for the issues that warrant concern.

Together, the aforementioned themes provided a basis for athlete monitoring with respect to injury and load and the workload- injury relationship in professional basketball. By understanding the implications of load on common lower limb injuries in basketball, and having effective methods for quantifying these loads, as well as the overall magnitude and prevalence of injuries, coaches and support staff can use these strategies with their own teams in order to better monitor and prescribe appropriate training loads while reducing overuse injuries over the course of a season.

## **Limitations**

The following limitations of this thesis include:

- . The accelerometer-based data is a surrogate measure of load.
- . Conflicting injury definitions between our research and other studies made direct comparison in the magnitude and prevalence of injuries difficult.
- . Though all of the athletes in the study had a relatively high response rate for the self-reporting questionnaire, we were unable to control for the potential that they may have been less willing to report overuse injury problems using the questionnaire if they felt it may jeopardize their selection to play.
- . Due to the team's travel schedule and the number of accelerometers available, the accelerometer data could not be modeled against the injury data.
- . Due to the relatively small sample size and data from only a single season, some of the athletes did not display mean trends (workload-injury) in order for a clear model to be developed. Four athletes had few or no injuries over the season, and therefore, no clear relationship emerged from their data. Additionally, three athletes had previous injuries and illnesses which resulted in insufficient exposure to high workloads throughout the season, meaning trends for these players could not be properly assessed.
- . Teams need to be aware that in order to be able to effectively create a training load-injury model for their athletes, data would need to be collected across multiple seasons.
- . Game-based bilateral lower limb load and steps/min data were not included

due to the professional basketball league's current technology regulations.

. Only the acute:chronic workload calculation was used in determining workload ratios, though other calculations are available.

## **Future Research Directions**

The main outcome of this thesis was to quantify lower limb injury and training load and the relationship between training loads and injuries in male professional basketball players. Based on the practical outcomes that resulted from this thesis, the following suggestions for future research include:

- . Techniques for assessing mechanics in-game in order to facilitate injury prevention and screening strategies.
- . Frequent monitoring of cumulative lower limb loads may be useful in conjunction with the OSTRC questionnaire for detecting changes requiring further attention.
- . Multi-centre collaborations are needed to generate a larger sample size with multiple teams across several seasons in order to describe the load-injury relationship with more certainty.
- . Monitoring bilateral lower limb loads across both training and competition over the course of multiple seasons.
- . Modelling bilateral lower limb load data alongside internal workload measures as well as injuries may be beneficial for teams seeking to increase athlete physical preparedness while mitigating injury risk.
- . Develop and test a workload-injury prediction model to determine its efficacy in the sport.
- . Based upon the way in which the modelling was performed for work load-injury study, the random effect in the model specifies that each of the athletes' trends should have different intercepts through the y-axis. This allows for each athlete to have the same sweet spot in terms of the workload ratio, but each also has their own likelihood of injury at each of the workload ratios. It may be advantageous to collect a greater amount of data using the same modelling protocol as outlined in the study, adding in a random effect for different slopes for different athletes which would allow coaches and performance staff to identify individualized workload ratio 'sweet spots'.

## **Conclusion**

This thesis demonstrates a number of methods and metrics for quantifying training load and injury which can be used for effective monitoring in professional men's basketball. These provide tools that enable coaches, medical and support staff to monitor athletes so as to be able to prescribe training loads in conjunction with using a more realistic injury surveillance method in order to improve athletes' preparedness at the lowest possible risk of injury. The objective data collected through the application of these methods and metrics may provide beneficial information to help guide best practices with respect to training, injuries, rehabilitation, and performance outcomes. Future research building upon the ideas presented in this thesis may further our understanding of the relationship between load and injury in professional men's basketball.



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functional hip joint centre and a mean helical knee axis. J Biomech. 2003;**36**(8):1159-68.

# APPENDIX 1. CONFERENCE ABSTRACT

## A novel method to quantify cumulative lower limb loads using wearable sensors

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### Aim

To define a novel metric to quantify cumulative lower limb loads using wearable accelerometers and to use this metric to identify bilateral load profiles in professional basketball players.

### Methods

Eight male professional basketball players volunteered to participate in this study (mean  $\pm$  SD: age,  $24.4 \pm 4.7$  years; height,  $194.9 \pm 7.6$  cm; body mass,  $96.3 \pm 11.6$  kg). All players wore bilateral inertial sensors (IMeasureU Ltd., New Zealand) on the distal-medial third of their tibias during training. Tri-axial accelerometer data were sampled and logged at 1000 Hz for the entire training session of 60 mins. The peak resultant acceleration recorded during every foot strike of activity served as a surrogate measure of impact load. Impact loads were binned into 2g increments (from 2 to 16g). A cumulative load score was then calculated using an adapted tissue load equation [1], as follows:

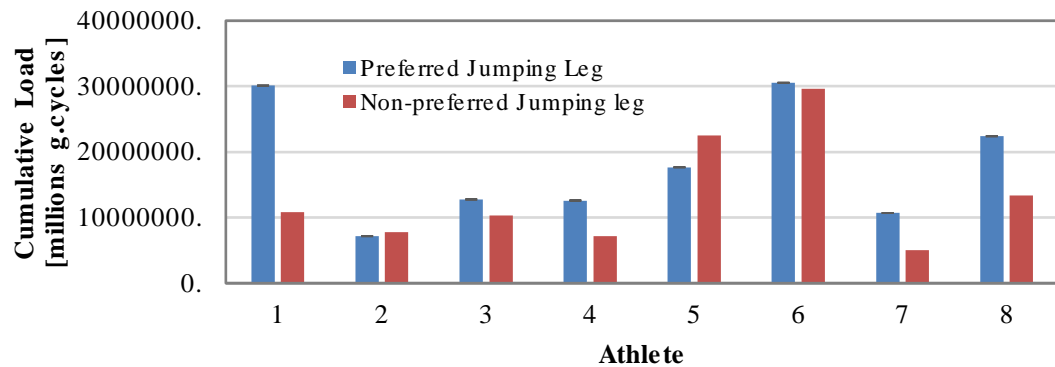
$$\text{Cumulative Load} = \sum (\text{impact load [g]})^4 \dot{Y}(n \text{ cycles})$$

The exponential in this loading metric accounts for the fact that skeletal tissue is influenced more by load magnitude compared to number of cycles [1]. The percent difference (preferred jumping leg-non-preferred) was calculated to determine differences in bilateral load profiles.

### Results

Large differences in bilateral loading profiles were observed across the eight athletes (Fig 1). Two athletes displayed symmetrical loading patterns (difference = 3% and 8%), whilst others experienced greater loading on their preferred side (difference =

21% to 94%). Across the same 60 min training session we observed a four-fold range in cumulative load from 7 to 30 million g.cycles (Fig.1).



**Figure 1. Cumulative lower limb loading of eight athletes observed over a 60 min training session. Percentage indicates difference between preferred and non-preferred jumping leg.**

## Conclusions

We have presented a novel metric to account for cumulative lower limb loading, based upon a mechanobiological understanding of skeletal tissue adaptation. This cumulative load metric is easy to implement in training and competition using wearable sensors and can identify load exposure and differential loading between limbs. We are currently using this metric to track athletes over a season and determine whether cumulative loading predicts load-related skeletal injury.

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## APPENDIX 2. CONFERENCE ABSTRACT

### **The application of a simple surveillance method for early detection of overuse injuries in professional basketball.**

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The extent and severity of overuse injuries in professional basketball can be difficult to determine, due to methodological differences in assessing and monitoring them. A negative association between injuries and team success has been established in a number of professional sports including soccer and Rugby Union. Additionally, overuse symptoms may indicate an athlete's response to imposed workloads and their ability to tolerate these loads.

**PURPOSE:** The purpose of this study was to assess the prevalence of common basketball-specific overuse problems using a self-reported questionnaire, over the course of a single basketball season. The secondary aim was to assess the utility of the questionnaire for early injury detection and prevention. **METHODS:** A 21-week prospective cohort study was conducted including 13 participants from a single professional men's basketball (Australian Basketball League) team during the 2015-2016 season. Data on overuse injuries in the ankle, and knee were collected every week using the Oslo Sports Trauma Research Centre Overuse Injury Questionnaire alongside injury reports from the team medical staff. Using a logistic regression model, the results of the questionnaire were compared to actual injuries diagnosed by the team physiotherapist in the subsequent week in order to determine if questionnaire overuse symptoms were reported preceding actual injuries. **RESULTS:** The mean weekly prevalence of self-reported overuse injuries was (ankle=12; knee=25). Players who self-reported overuse symptoms were more likely to be diagnosed with a subsequent overuse injury (Table 1). **CONCLUSIONS:** The self-reported questionnaire was able to predict actual knee and ankle injuries one week prior to



actual injury onset. This may be useful in determining the dose-response relationship between training and overuse injuries. **PRACTICAL APPLICATION:** Overuse injuries can be monitored and detected using the simple overuse questionnaire method applied in this study. This method may be useful in assessing the need for injury prevention and rehabilitation protocols for a team. It could also be used for determining the athletes' individual preparedness and response to loading and determining proper training interventions in order to improve their ability to handle loads and to work towards reducing the onset of overuse injuries. These findings support the use of simple overuse injury monitoring strategies within professional basketball as a means of early detection and prevention.

**Table 1. The effect of self-reported overuse symptoms on the likelihood of subsequently diagnosed overuse injury of the ankle and knee.**

	95% C.I. for Odds Ratio			
	p	Odds Ratio	Lower	Upper
Self-reported knee symptoms	>0.001*	13.9	3.75	51.5
Self-reported severe knee symptoms	0.002*	9.85	2.23	42.3
Self-reported ankle symptoms	0.066	3.84	0.916	16.1
Self-reported severe ankle symptoms	0.001*	37.4	4.66	300

C.I. = confidence interval; \*Denotes statistically significant predictability of the variable ( $p < 0.05$ ).