# A CRITICAL EVALUATION OF BIOMECHANICAL RISK FACTORS FOR ACL INJURIES DURING DYNAMIC ACTIVITIES

RAIHANA SHARIR

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

June 2018

# Abstract

For injury screening to effectively identify individuals with at-risk behaviours, risk factors should be identified and validated carefully through appropriate prospective study designs. In the context of injury prevention in sport, the main aim of screening is to draw a line between those who are at risk of getting injured and those who are not. In order to effectively screen for anterior cruciate ligament (ACL) injury risk, injury screening should not be based on a singular observation in a single task as it is unlikely to effectively identify those who are at risk with acceptable sensitivity and specificity. Observations of ACL injury could be evaluated through a more mechanism-informed risk factors as this may provide a better justification of an individual's movement pattern. If an individual who is at risk would demonstrate a particular behaviour across different tasks, this collection of variables characterising an individuals' at-risk behaviours across tasks could form an individual's "movement signature". This thesis therefore aimed to critically evaluate the biomechanical risk factors for non-contact ACL injury during dynamic sporting activities and to explore some novel approaches to characterising movement characteristics for screening.

Through a systematic review, the first study in this thesis critically evaluated the current research trends on the *in vivo* biomechanical risk factors of the ACL injury in dynamic activities and identified a lack of high quality (level 1), prospective evidence. Only one prospective cohort study was identified; therefore, more prospective cohort studies are required as research since the time of this systematic review did not provide further prospective evidence. Study two sought to develop more prospective evidence but unfortunately no ACL injuries were observed therefore, no new biomechanical risk factors for ACL injury could be identified. Utilizing the data collected from the prospective cohort, study three led to the development of a novel approach of injury screening by verifying the existence of individual movement signatures. The task-invariant movement signatures were also able to identify at-risk movement behaviour. Further exploration of mechanism informed multi-planar variables in study four showed that task-invariant movement signatures also exist in multi-planar variables, and may better inform at-risk behaviours.

This thesis has furthered the understanding of biomechanical risk factors and moved towards the development of more effective injury screening tools.

# Acknowledgements

I am very fortunate and lucky to have been supervised by an incredibly supportive team whom with their guidance and expertise has made this doctoral thesis a success. I would like to take this opportunity to express my sincere appreciation for their endless support, feedback, dedication and trust that they have given me for this past four and a half years. And for always believing in me and giving me the opportunity to learn and shine.

Firstly, greatest appreciation to my director of studies *Dr Mark Robinson* whom has given me endless support and supervision throughout the years. The countless meetings and discussions we had and the prompt feedback that I got (even on weekends!) showed his dedication towards shaping me into a critical thinker and passionate researcher. To *Dr Jos Vanrenterghem*, my second supervisor whom I have learn that one can have 'doing research' as a hobby. Thank you for the enthusiasm, inspiration and challenges you've given me in ensuring the success of this doctoral research. To *Professor Keith George,* my third supervisor for your guidance and expertise in the process of constructing the systematic review and the moral support you've given throughout the years.

I would also like to acknowledge the *Faculty of Sport Science and Recreation, University Teknologi MARA, Malaysia* and the *Ministry of Education Malaysia* for the funding of the first three years of my PhD program. Also, a big thank you to my research co-investigator, *Radin Rafeeuddin*; who together with me started the Liverpool Knee Injury Study. I could not have conducted our extensive testing sessions without you therefore, I am very grateful and it was a pleasure working alongside you. To all my 'lab mates' in the Biomechanics Research laboratory past and present, it has been quite an adventure sharing my PhD journey with all of you and thank you for the encouragement and moral support you guys have given me throughout my ups and downs (you know who you are!).

Most importantly, my heart and soul who has brought me to this world and believed in me since I was a child; my parents, *Rahmah Atil* and *Sharir Ismail*. Thank you mum and ayah for never saying no to my sporting activities and sending me to trainings and competitions and for showering me with unconditional love and support. To my siblings, *Aca*, *Ain* and *Kamal* for the encouragements and believing that your eldest sister can do it. To my handsome partner *Tom Ross*, thank you for being there for me during the good times and the bad, and for the continual support and belief. To the *Ross* family (and *Harvey* too!), for opening up your home to me and making me feel part of your family.

# Table of Contents

# List of Publication and Communication

**Publications**

i. Sharir R, Rafeeuddin R, Staes F, Dingenen B, George K, Vanrenterghem J, Robinson MA. Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors. Clin Biomech (Bristol, Avon). 2016 Aug;37:34-43. doi: 10.1016/j.clinbiomech.2016.05.017

ii. Sharir R, Rafeeuddin R, Staes F, Dingenen B, George K, Vanrenterghem J, Robinson MA Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors – Response to Letter to the Editor. Clin Biomech (Bristol, Avon). 2016 Jul 25. pii: S0268-0033(16)30105-X. doi: 10.1016/j.clinbiomech.2016.07.006

iii. Sharir R, Vanrenterghem J, Robinson M, et al. What separates an individual at risk of ACL injury? A first step towards an ACL-risk movement passport. Br J Sports Med 2017;51:388

**Oral Presentations**

i. Sharir R, Rafeeuddin R (April 2014). Identification of biomechanical and neuromuscular risk factors for knee injury during dynamic activities: A Prospective Study. *LJMU Research Institute Sports and Exercise Sciences Seminar 2014: International Student Presentation Day*. Liverpool John Moores University, United Kingdom.

ii. Sharir R (April 2015). Mapping Current Research on the biomechanical risk factors for non-contact ACL injury: A systematic review. *LJMU Research Institute Sports and Exercise Sciences Seminar 2015: International Student Presentation Day.* Liverpool John Moores University, United Kingdom

iii. Sharir, R, Rafeeuddin, Radin, Robinson MA, Vanrenterghem J (May 2015). Mapping Current Research on the biomechanical risk factors for non-contact ACL injury: A systematic review. *British Association of Sports and Exercise Science: Biomechanics Interest Group Meeting*. University of Roehampton, United Kingdom.

iv. Sharir, R, Rafeeuddin, Radin, Robinson MA, Vanrenterghem J (June 2015). Mapping current research on the biomechanical risk factors for non-contact acl injury: A systematic review. *Faculty of Science Research and Seminar Day 2015.* Liverpool John Moores University, United Kingdom. **(2$^{nd}$ Runner Up Winner for Best Oral Presentation)**

v. Sharir, R (April 2016). Knee Injury: Is it the end of a sporting career? 3 Minute Thesis Competition, *Graduate School Conference 2016.* Liverpool John Moores University, United Kingdom. **(1st Prize Winner)**

vi. Sharir R, George K, Vanrenterghem J, Robinson MA. What can separate an individual at risk? A first step towards an ACL movement passport. (March 2017) *International Women's Day Conference*. Liverpool John Moores University, United Kingdom.

vii. Sharir R, George K, Vanrenterghem J, Robinson MA. What separates an individual at risk of ACL injury? A first step towards an ACL-risk movement passport. (March 2017) *IOC World Conference Prevention of Injury & Illness in Sport 2017*, Grimaldi Forum, Monaco.

viii. Sharir R, Rafeeuddin R, Vanrenterghem J, Robinson MA. How consistently do prospective ACL risk factors classify individuals in different tasks? (May 2017) *British Association of Sports and Exercise Science: Biomechanic Interest Group Meeting.* Portsmouth University, United Kingdom.

ix. Sharir R. Identification of biomechanical risk factors for the anterior cruciate ligament injuries during dynamic activities. (October 2017) *British Federation of Women Graduates, North West Region. Annual Presentation Day.* New Brighton, United Kingdom. **(1st Runner Up Winner)**

# List of Tables

# List of Figures

**Chapter 2**



**Chapter 3**



**Chapter 4**



**Chapter 5**

**Chapter 6**



**Chapter 7**

# List of Abbreviations, Acronyms and Symbols

| | |
|---|---|
| $\rho$ | Spearman's rho |
| 2D | two dimensional |
| 3D | three dimensional |
| ACL | anterior cruciate ligament |
| ACLD | ACL deficient |
| ACLR | ACL reconstruction |
| BDVJ | bilateral drop vertical jump |
| COM | centre of mass |
| CoP | centre of pressure |
| DOM | dominant |
| EMG | electromyography |
| F | female |
| $GRF_{sag}$ | Ground reaction force sagittal plane forces |
| $HM_{nsag}$ | hip moment non-sagittal plane moment vector |
| INJ | injured |
| KAA | knee abduction angle at initial contact |
| $KM_{nsag}$ | Knee moment non-sagittal plane moment vector |
| M | male |
| MD | medial displacement |
| NDOM | non-dominant |
| pKAM | peak knee abduction moments |
| pKFA | peak knee flexion angle |
| pVGRF | peak vertical ground reaction force |
| ROM | range of motion |
| SLDVJ | single leg drop vertical jump |
| SLHOP | single leg hop |
| SS | sidestep |
| UNINJ | uninjured |

# Glossary of Terms

| | |
|---|---|
| Associative study | Provides a lower level of evidence because these cannot measure risk factors directly and so instead associates other variables with known risk factors. They can help to understand how known risk factors are influenced by other variables that have not yet been shown prospectively as risk factors themselves. Level of evidence. |
| Highly-ranked movement signatures | Movement signatures that ranked in the $4^{th}$ and $5^{th}$ quintile |
| Initial contact | The time instant when the foot made contact to the ground as it passes 20 N threshold on the force platform |
| Median-error line | Median possible value of the absolute sum of error score which was annotated with a white line |
| Movement Signature | A consistent quintile rank across tasks in a particular risk factor where all tasks ranked in the same quintile or 3 tasks ranked in the same quintile, with 1 task ranked ± one difference to the majority quintile. |
| Multi-planar | Multiple planes |
| Omni-variate approach | Observation of several tasks and parameters in search of a risk profile rather than individual risk factors |
| Poli-variate approach | One risk factor/parameter observed across multiple tasks |
| Prospective study | Observe a large number of uninjured athletes and then monitor their injury status over a period of time. Those athletes that become injured can then be compared to the uninjured group in an attempt to identify differences with a predictive value commonly called risk factors. Level of evidence 1. |

| | |
|---|---|
| Retrospective study | A study design that takes a look back at the effect of an event that occurred in the past and typically makes comparisons to a control group. In a typical retrospective ACL study, investigators would compare ACL injured or reconstructed athletes to an uninjured control group. Level of evidence 2. |
| Take off | The time instant when the foot comes off the ground as it passes 20 N threshold on the force platform |
| Uni-planar | Single plane |
| Uni-variate approach | Several risk factors observed within one particular task |
| Weight acceptance | A phase in sidestepping from initial contact to the end of the passive phase (Dempsey et al., 2007) |

# CHAPTER 1

General Introduction

# 1.0 Background

Excessive dynamic loads or forces experienced by the knee beyond its capability can cause injury, particularly to the ligament. In highly demanding sporting activities, anterior cruciate ligament (ACL) injury is one of the most debilitating (Agel, Evans, Dick, Putukian, & Marshall, 2007; Bjordal, Arnly, Hannestad, & Strand, 1997). In the United Kingdom alone, 2836 cases of ACL injury were registered by the National Ligament Registry in 2016 (Gabr, De Medici, & Haddad, 2017) and around half of these patients then had a surgical ACL reconstruction. The cost of ACL reconstruction is ~£3000 - £3500 if performed through the National Health Service, and higher in private hospitals (estimated to be between £3500 - £11000) ("How much does an... ACL reconstruction cost", 2017). The high incidence of ACL injury is not only devastating in itself but it can also have long-term effects such as knee osteoarthritis (Fu & Lin, 2013; Louboutin et al., 2009). The consequences of an ACL injury not only affect a patient's health and quality of life, but due to the long recovery time and high cost of surgery, it also has a heavy economic burden and wider societal impact (Mather et al., 2013). ACL injuries therefore present both a relevant financial and scientific challenge.

The main role of the ACL is to stabilize the knee by restraining forward movement of the tibia and prevent rotational load to the knee (Bicer, Lustig, Servien, Selmi, & Neyret, 2010). Up to 70% of primary ACL injuries are non-contact in nature and typically happen during rapid dynamic activities such as sudden stops, changes of direction, jump landings, pivoting, decelerating and side cutting manoeuvres (Boden, Dean, Feagin, & Garrett, 2000; Yu & Garrett, 2007). Furthermore, females have generally been observed to have more ACL injuries than males (Agel, Arendt, & Bershadsky, 2005; Messina, Farney, & DeLee, 1999; Tranaeus, Gotesson, & Werner, 2016) however, it is still unknown if the injury mechanism between females and males are similar. It is well established that ACL injuries are multi-factorial, including hormonal, genetic, anatomical, neuromuscular and biomechanical factors (Shultz et al., 2012). By screening risk factors, this could hopefully intervene and prevent injury occurrence (D. A. Padua et al., 2015) although this is not guaranteed (Smith et al., 2012). Eventhough it may seem like a lot of work has been done in this field, ACL injury rates are not declining (Agel, Rockwood, & Klossner, 2016); therefore, more effective screening is needed to prevent ACL injuries from occurring.

Over the last decade, a large number of studies have used *in vivo* biomechanical methods to investigate risk factors between specific biomechanical parameters and risk of non-contact ACL injury. Risk factors are predictive parameters established from prospective cohort studies, where the parameters showed meaningful differences between ACL injured athletes compared to uninjured athletes. One advantage of focussing on biomechanical risk factors is that they are modifiable (Lephart et al., 2005; Myer, Ford, Palumbo, & Hewett, 2005). As such, some injury prevention programs may be able to effectively reduce the risk of injury, though these prevention programs have typically been sex-specific, sport focused, within certain populations, for a certain level of play, or often including multiple training components, which makes injury prevention programs almost impossible to replicate (Monajati, Larumbe-Zabala, Goss-Sampson, & Naclerio, 2016; Taylor, Waxman, Richter, & Shultz, 2015). Similarly, positive outcomes might be limited or not detectable, possibly explaining why in some previous studies no significant changes in ACL injury rates were seen (Myklebust et al., 2003; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008). The challenge of identifying individuals at risk of ACL injury is substantial because of low injury rates and a lack of predictive power of existing individual risk factors (Bahr, 2016). In an attempt to move this field of work forwards, we identified three important directions at the outset of the work presented in this thesis: (1) there was a perception that more prospective data on biomechanical injury risk was needed, (2) there was the belief that the traditional approach in terms of how to establish biomechanical risk was in need of a paradigm shift in search of more effective screening modalities, and (3) the multi-planar mechanisms of injury require multi-planar risk observations rather than the traditional uni-planar observations. Each of these directions will be briefly introduced below.

Despite many studies describing "risk factors" there has been a misconception that there are a large number of prospectively-informed biomechanical risk factors for non-contact ACL injury (Hughes, 2014). However simply associating risk factors to ACL injury is not equivalent to identifying new biomechanical risk factors. Many typically observed parameters include smaller knee flexion angle, bigger knee abduction moment, bigger knee abduction angle and bigger knee extension moment at key events e.g. initial contact, take-off or at their maximum extent (Hughes, 2014), but most of these are undesirable movement characteristics rather than prospectively-informed risk factors. Therefore, a review and quality assessment of existing biomechanical studies was needed, as well as further prospective evidence to both identify and extend what we know about the risk factors for ACL injury.

The use of biomechanical variables for screening or injury prediction purposes has focused on using a single variable in a single task. There is often no wider consideration of an athlete's behaviour across tasks or whether multiple variables across multiple tasks show an athlete to be at risk. Perhaps by evaluating commonalities of at-risk behaviour across tasks one might be able to identify with greater certainty those individuals who really are at increased risk of injury compared to their peers. If a risk factor were more representative of the individual's generic movement strategy, i.e. denoting a signature of their generic behaviour, then that would provide a stronger justification for movement patterns than a risk factor that only reflects an individual's strategy to performing one specific task. In other words, a risk factor that can consistently identify high-risk individuals regardless of which task they are doing would be considered more robust for screening purposes. However, this approach to risk identification has not been applied before.

It is well established that non-contact ACL injuries do not occur through motion and loading in a single plane (Donnelly et al., 2012; McLean, Huang, Su, & Van Den Bogert, 2004; Quatman, Quatman-Yates, & Hewett, 2010) however, all established biomechanical risk factors have been uni-planar observations. Observing multi-planar loading during dynamic movements could potentially provide a more mechanism-informed screening process.

In summary, many studies appear to have identified biomechanical risk factors but which risk factors are prospectively-informed and the appropriateness of these risk factors for identifying individuals at risk is unclear. The work presented in this thesis provides new insights into our understanding of biomechanical risk factors for ACL injury in dynamic sporting activities by providing a new task-invariant approach to screen for ACL injury risk that could lead to a paradigm shift in search of more effective screening modalities. Moreover, by observing multi-planar variables, better informed mechanism-related injury screening should be considered rather than observing traditional uni-planar observations. A better justification of an individual's at-risk movement behaviour is vital for researchers and practitioners to develop more effective injury screening. As such, the work presented in this thesis reflects a critical and rigorous attempt to obtain a better understanding of biomechanical risk of non-contact ACL injury, ultimately helping the field forward towards improved screening and prevention.

# CHAPTER 2

## Literature Review

*This chapter aims to review the research evidence relating to biomechanical risk factors for non-contact anterior cruciate ligament injury. The review will cover (i) the epidemiology of non-contact ACL injuries, (ii) the framework of injury prevention, (iii) mechanisms of non-contact ACL injury in dynamic activities, (iv) screening methods used to predict ACL injury and lastly (vi) the biomechanical risk factors of non-contact ACL injury*

## 2.1 Epidemiology of non-contact ACL injury

### 2.1.1 Anatomy of ACL

One of the biggest and most intricate joints in the body, the knee; is surrounded by the femur, patella, tibia and fibula. The femur and tibia are connected at the knee joint by the knee ligaments. Ligaments are tough, flexible fibrous connective tissue which connect bones together. The knee joint consists of four main ligaments (Figure 2.1) that keep the knee within its normal range of motion; (i) anterior cruciate ligament (ACL), (ii) posterior cruciate ligament (PCL), (iii) medial collateral ligament (MCL) and (iv) lateral collateral ligament (LCL).

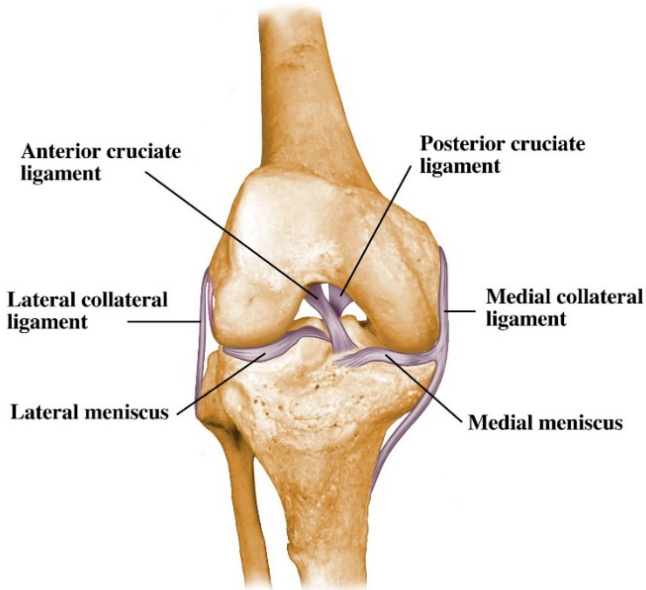



Figure 2.1 Frontal view of the knee ligaments and meniscus.



The ACL connects the femur and tibia and is anteriorly situated in the knee joint. The ACL provides stability to the knee and prevents anterior tibial translation and rotational load (Bicer et al., 2010). Between $30^o$-$90^o$ knee flexion, the ACL absorbs 85% of the anterior translation load and 75% at full extension (Butler, Noyes, & Grood, 1980). It originates at the posteromedial surface of the lateral femoral condyle and attaches at its insertion on the anterior intercondylar fossa area on the tibia. It is made up of the anteromedial bundle and the posterolateral bundle. Each of these bundles has its own function though several studies have observed the anteromedial bundle to be stronger (Butler et al., 1992; Duthon et al., 2006; Girgis, Marshall, & Monajem, 1975; Kweon, Lederman, & Chhabra, 2013). At 90 degrees of knee flexion (Figure 2.2), the anteromedial bundle tightens while the posterolateral bundle slackens and vice versa during full extension (Bicer et al., 2010; Duthon et al., 2006; Markatos, Kaseta, Lallos, Korres, & Efstathopoulos, 2013). Younger specimen knees (~22-35 years old) have approximately 2200 N in tensile strength but lesser strength was seen in older adults and/or with repetitive loads (Noyes & Grood, 1976; Woo, Hollis, Adams, Lyon, & Takai, 1991).

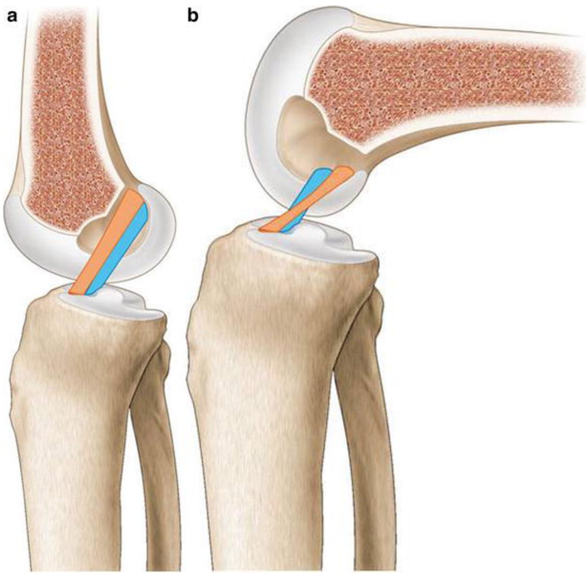



Figure 2.2 Sagittal plane view of ACL bundle behaviour at knee (a) extension (b) 90$^{o}$ flexion. Anteromedial bundle in orange, posterolateral bundle in blue.



### 2.1.2 ACL injury incidence

ACL injury is one of the most common in the sporting world other than injury to the ankle, face, or hamstring (Hootman, Dick, & Agel, 2007; Nielsen & Yde, 1989; Wong & Hong, 2005). Annually, an estimation of 350,000 ACL reconstruction surgeries are performed in the United States (Nessler, Denney, & Sampley, 2017) and increasing number of ACL injuries are seen each year (Buller, Best, Baraga, & Kaplan, 2015). On account of the high cost of surgical ACL reconstruction, it does not only affect the individual's health for their lifetime (Filbay, Culvenor, Ackerman, Russell, & Crossley, 2015) but is also a heavy economic burden to society (Mather et al., 2013). The high incidence of ACL injury itself is not only devastating but can also have long-term effects on the knees such as through osteoarthritis (Gianotti, Marshall, Hume, & Bunt, 2009; Lohmander, Ostenberg, Englund, & Roos, 2004; Neuman et al., 2008). Not only that, it could also impact an athlete's sporting career as they would be unable to compete for up to one year and when return (only 80%), they would rarely perform as well as they did prior to injury (Kester, Behery, Minhas, & Hsu, 2017).

Up to 70% of ACL injuries occur during sport-related movements and do not involve any contact with other players (Boden et al., 2000; Griffin et al., 2000). They are most commonly seen in dynamic types of sport such as in football, netball, hockey, basketball and handball, with the incidence higher during competition than training sessions (Joseph et al., 2013; Walden, Hagglund, Werner, & Ekstrand, 2011). Many studies have shown that females are more likely to be injured than males by ~ 4-6 fold and their injury incidence rate during match-play is also higher than males (Agel et al., 2005; Arendt & Dick, 1995; Renstrom et al., 2008; Walden et al., 2011). There are a number of possible reasons for this including a female's build. Anatomically females typically have smaller ACL's than males (Renstrom et al., 2008). The width and shape of the femoral notch is determined by the size and location of the ACL (Ireland, 2002; Sutton & Bullock, 2013) and evidence has suggested that a smaller femoral notch and smaller ACL leads to higher risk of injuring the ACL, even regardless of sex (Renstrom et al., 2008; Sutton & Bullock, 2013). In addition, due to having a wider pelvis, females generally have a greater quadriceps angle (Q angle) than males (Nguyen & Shultz, 2007; Woodland & Francis, 1992). A bigger standing Q angle can result in an increased hip varus, knee valgus and foot pronation – a hazardous position for the ACL (Griffin et al., 2000; Nguyen & Shultz, 2007; Woodland & Francis, 1992). The greater incidence of non-contact ACL injuries in females has led to a concentration of studies involving females in the literature.

## 2.2 Framework for injury prevention research

In order to prevent the occurrence of an injury, systematic steps should be taken. In 1992, van Mechelen and colleagues developed one of the most cited models of sports injury prevention (van Mechelen, Hlobil, & Kemper, 1992), which was later advanced into the Translating Research into Injury Prevention Practice (TRIPP) framework (Finch, 2006). The progression and development of injury prevention research typically follows the stages within the framework. The four-step sequence model has been the foundation for many injury prevention researches including the more recent ACL-focused injury prevention framework proposed by Donnelly et al. (2012). In his ACL injury prevention framework, he provides more detailed stages in preventing an ACL injury (Figure 2.3).

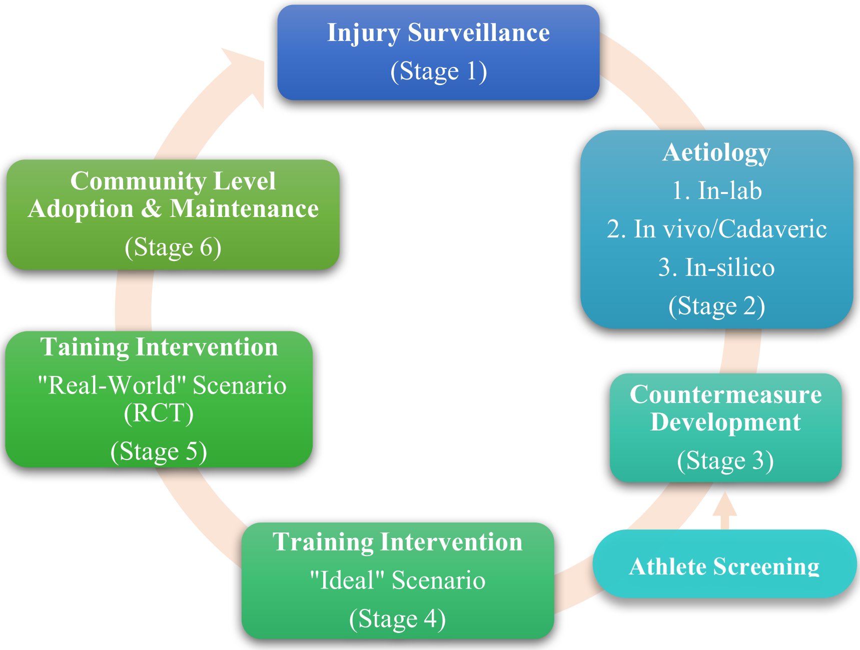



Figure 2.3 Donnelly et al. (2012) non-contact ACL injury prevention framework

Tailored from the TRIPP model (Finch, 2006), the first stage of the framework starts at the very beginning of the sporting activity itself with injury surveillance. Incidence, injury rates, and most common movements or tasks related to ACL injuries are observed and identified in the first stage. Stage 2 consists of identifying the injury mechanism and risk factors through *in vivo, in vitro* or *in silico* studies. Once these have been identified, a countermeasure development or a preventative measure to reduce the risk of the injury can be developed in Stage 3. Donnelly et al. (2012) proposed that several areas such as the technique and neuromuscular support should be concentrated on to decrease the biomechanical risk factors associated with ACL injury. Once countermeasures are established, a sport-specific or training-specific protocol can be developed (Stage 4). Once developed, the next step is to test this intervention in a 'real-world' environment (Stage 5) and evaluate how well the lab-based outcomes translate into the training environments. The next stage (Stage 6) is the maintenance of this intervention which may require future research to evaluate how well the intervention was accepted within the community. By the end of this stage, an evaluation of the targeted reduction of ACL injury rates should be the aim of the next assessment (Stage 1). Finally, if carefully followed, this framework may lead to reduced ACL injury rates (Donnelly et al., 2012). This thesis is based within Stage 3 of Donnelly's non-contact ACL injury prevention framework.

## 2.3 Biomechanical mechanisms of non-contact ACL injuries in dynamic activities

ACL injuries are likely to occur during dynamic activities that involve sudden stops, jump landings and sudden changes of direction in addition to improper mechanics and execution of these dynamic movements (Alentorn-Geli et al., 2009; Boden et al., 2000; Sanna & O'Connor, 2008; Yu & Garrett, 2007). As aforementioned in the injury prevention framework (Donnelly et al., 2012), the injury mechanism should be identified. Understanding the ACL injury mechanism can be gained through a variety of study modes including *in vitro* (cadaveric work), *in silico* (computer simulations) and *in vivo* (observational studies) studies. Therefore, these approaches of studying the ACL injury mechanism will be briefly addressed in the following paragraphs.

Biomechanical *in vivo* experimental investigation consists of clinical, observational and laboratory methodologies (Quatman, Quatman, & Hewett, 2009). Sudden changes of direction (sidestepping), stops (deceleration) and landing from a jump are some of the common movements that lead to an ACL injury (Griffin et al., 2006). This is thought to occur between 17 to 50 milliseconds after initial foot contact (Alentorn-Geli et al., 2009; Boden et al., 2000; Boden, Sheehan, Torg, & Hewett, 2010; Griffin et al., 2006; Koga et al., 2011; Krosshaug et al., 2007). Small knee flexion angles (hyperextension), internal/external rotation of the tibia, anterior tibial translation, anterior shear force, high ground reaction forces and dynamic valgus collapse are mechanisms that contribute to ACL injury (Boden et al., 2000; DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Fleming et al., 2001; S. Y. Kim et al., 2015; Koga et al., 2011; Walden et al., 2011). When the knee is minimally flexed, the ACL is the only passive restraint to protect the knee against anterior tibial translation (Figure 2.4) (Butler et al., 1980; Grood, Noyes, Butler, & Suntay, 1981; Markolf, Graff-Radford, & Amstutz, 1978). A forceful load (i.e. quadriceps pull) at a nearly extended knee ($20^{o}$ to $30^{o}$ of knee flexion angle) can yield significant anterior tibial translation therefore increasing the ACL loading (Beynnon & Fleming, 1998; Butler et al., 1980; DeMorat et al., 2004; Hashemi et al., 2011; Markolf, Mensch, & Amstutz, 1976; Sell et al., 2007; Yu & Garrett, 2007) i.e. especially during landing from a jump. Excessive loading to the ACL may overstrain the ligament and result in partial or full tearing of the ligament (Alentorn-Geli et al., 2009; Boden et al., 2000; Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004).

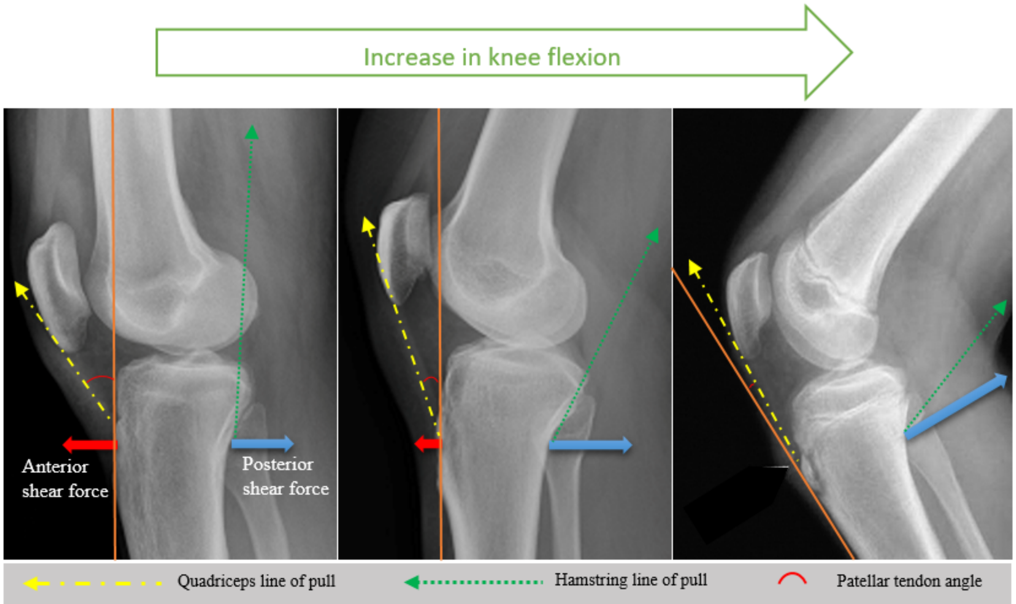



Figure 2.4 Patellar tendon angle and anterior shear force from quadriceps decreases as the knee flexion increases. Posterior shear force from hamstrings protects the ACL and increases with knee flexion.

*Image based on the figure of T. Kernozek, Torry, Shelburne, Durall, and Willson (2013)*

Hashemi et al. (2011) proposed the hip extension-knee flexion paradox as one mechanism for ACL injury. The knee and hip should typically flex simultaneously at landing in a normal condition; but during unstable landing, involuntary hip extension and knee flexion can occur (hip extension-knee flexion paradox) and when this happens, the tibia can translate anteriorly which increases ACL injury risk.

When an excessive dynamic load or force is exposed to the knee beyond its capability - typically higher than what the ligament can sustain (Lloyd, 2001), it increases the risk of injury to the ligament. *In vitro*, an increased strain on the ACL can be seen when valgus and internal rotation moments and anterior tibial translation are applied (Markolf et al., 1995; Shin, Chaudhari, & Andriacchi, 2011). Importantly, the magnitude of a single load alone leads to less ACL strain when compared to multi-planar (page xiv) combinations of load. Berns, Hull, and Patterson (1992) studied 13 cadaver knees to examine the effects of combined knee loading on ACL strain. Pairs of combined loads were applied at 0° and 30° flexion angle while a strain gauge measured ACL strain. They found a significantly greater strain in the anterior medial bundle of ACL when a combination of the anterior shear force at the proximal end of the tibia and a knee valgus moment were applied (Berns et al., 1992). Lesser strain was observed when the anterior shear force was applied alone (Berns et al., 1992). Markolf et al. (1995) also agreed that combined knee loading can produce greater ACL strain. 100 N of anterior tibial force, 10 Nm of abduction and adduction moment and 10Nm of internal and external tibial torque was applied to 14 cadaveric knees and the resultant forces on the ACL were recorded while the knees were extended from 90° of flexion to 5° of hyperextension. At full extension and hyperextension, the combination of internal tibial rotation moment and abduction moment significantly increased the forces in the ACL. These *in vitro* studies have provided us with important insights of what is actually happening to the knee when a researcher has full control of the loads applied to the knee. However, it lacks the *in situ* element of the injury mechanism which typically happens during dynamic activities and does not account for the effect of muscle forces in mitigating the strain; therefore, in vitro studies may not effectively demonstrate the actual ACL loading generated from the movements of a living human (Shimokochi & Shultz, 2008).

Prediction of ACL loading from *in silico* studies has helped increase our understanding on the behaviours and dynamic loading of the ACL. Though this effort may not represent an actual *in situ* observation it does make it possible to assess and simulate a dangerous situation or movements that can rupture ACL (Gerritsen, van den Bogert, & Nigg, 1995; McLean, 2008). Nonetheless, computer simulation studies also support the idea that multi-planar loading is required to rupture the ACL (McLean, Huang, et al., 2004). A dynamic knee simulation study driven by *in vivo* human loading data has found similar results to the previously mentioned *in vitro* studies (Shin et al., 2011). A validated three-dimensional dynamic knee joint model was used to predict ACL strains and the study observed a greater increase of ACL strain in a combination of knee abduction and internal rotation moments, than either load alone (Shin et al., 2011). In addition, findings by McLean, Huang, et al. (2004) observed that the knee joint forces in the sagittal plane might not be able to tear the ACL, whereas a combination of loads in the frontal and transverse plane produced greater strain that could potentially rupture the ligament. ACL injury mechanisms proposed in all modes of study (*in vitro*, *in silico* and *in vivo*) provide substantial evidence that the injury mechanism is inherently multi-planar.

## 2.4 Biomechanical risk factors for non-contact ACL injury

A risk factor can be used to identify athletes or participants who are at-risk of injury (Offord & Kraemer, 2000). Risk factors are predictive parameters established from prospective cohort studies, where the parameters showed meaningful differences between ACL injured athletes compared to uninjured athletes. Non-contact ACL injury risk factors can be extrinsic, i.e. playing surface, weather, shoe types and sporting equipment; or intrinsic, i.e. sex, knee joint laxity, ACL size, hormonal change and psychological factors. This debilitating injury clearly has a multifactorial aetiology. However, conflicting findings have been seen in identifying risk factors for ACL injury. According to the consensus statement from the ACL retreat VI (Shultz et al., 2012) non-contact ACL injuries are likely multifactorial and likely including hormonal, genetic, anatomical, neuromuscular and biomechanical factors. Rather than dividing them as extrinsic versus intrinsic, these multifactorial risk factors can also be sub-divided into "modifiable" factors and "non-modifiable" factors. Non-modifiable risk factors are factors that cannot change such as the genetics, sex, notch width, ACL size or ligamentous laxity. Therefore, in an injury prevention context it is only practical and realistic for researchers to investigate modifiable risk factors which can be altered through intervention, such as knee flexion angles or abduction moments.

The 17-50 ms window within which ACL injuries are likely to occur is when rapid braking occurs in dynamic sports, hence researchers use a variety of dynamic tasks inside and outside the laboratory to examine ACL injury risk behaviours (Alentorn-Geli et al., 2009; Boden et al., 2000; Boden et al., 2010; Griffin et al., 2006; Koga et al., 2011; Krosshaug et al., 2007). Such tasks include single-leg hop tasks, used to replicate sudden deceleration, or sidestepping manoeuvers, used to replicate rapid change of direction actions (Boden, et al., 2000). Studies have also focussed on bilateral drop vertical jumping. A seminal prospective study (Hewett et al., 2005) showed that knee abduction moment at landing was found to be the strongest predictor of ACL injury with 78% sensitivity and 73% specificity, alongside the knee flexion angle at initial contact and peak vertical ground reaction force. In addition, a more extended knee (small knee flexion) at landing was observed to be the cause of the increased vertical ground reaction force (Hewett et al., 2005). Other studies have suggested that a large knee valgus angle, small knee flexion angle, greater vertical ground reaction force, greater anterior shear force and greater knee abduction moment increase ACL injury risk significantly and are particularly higher in females than males (Chappell, Yu, Kirkendall, & Garrett, 2002; Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Ford, Myer, & Hewett, 2003; Lephart, Ferris, & Fu, 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001). In addition, it was also found that female athletes most frequently injure their non-dominant leg while male athletes most frequently injure their dominant leg (Brophy, Silvers, Gonzales, & Mandelbaum, 2010).

Using experimental observations to find predictors of injury that are valuable for screening can be achieved through prospective cohort studies. As a matter of fact, as outlined in the TRIPP framework (Finch, 2006), a prospective cohort study provides the strongest evidence for identifying an injury risk factor. As a prospective study follows individuals over time, and observes those who become injured, these studies allow the injured group to be compared against the healthy controls. These types of studies are needed to strengthen the development of intervention and prevention programs as the success of these programs is underpinned by a solid understanding of the risks associated with sustaining the injury as opposed to any surrogate or any indirect measure of injury risk. As a field of research progresses, it is desirable that the number of independent studies with a high level of evidence (such as prospective studies in this case) increases (Samuelsson et al., 2013). Despite the extensive studies describing biomechanical risk factors for non-contact ACL injury, the study design, consistency of methods and techniques of evaluating risk factors have not been examined in detail. Many studies compare risk factors interchangeably between males and females, transfer results across different tasks, focus on single uni-planar variables, or estimate risk indirectly rather than prospectively. This therefore warrants a review of the literature and consider further prospective determination of biomechanical ACL injury risk factors.

## 2.5 Screening for injury prevention

Utilising risk factors to distinguish individuals who are at risk of a condition or disease is the core process of screening. By identifying individuals who are at risk early, treatment or prevention programs can be implemented to prevent or reduce future illnesses or disease (Bahr, 2016; Dallinga, Benjaminse, & Lemmink, 2012; Gajic et al., 2011). In the context of injury prevention in sport, the main aim of screening is to draw a line between those who are at risk of getting injured and those who are not (Bahr, 2016; Dennis, Finch, Elliott, & Farhart, 2008; Gabbe, Bennell, Wajswelner, & Finch, 2004). The increasing number of ACL injuries has led to the vast increment of interest in injury prevention through screening (Klugl et al., 2010). Injury screening is usually done for everyone, but one can raise the question why injury prevention programs would not de facto be given to everyone regardless of a player being at-risk or not? Essentially, injury prevention programs are expected to be more effective in preventing injury when given and implemented to the individuals who are at risk, primarily increasing compliance to the program (Finch, 2006). Even if a reduction in injury risk would be seen across individuals who participated in a population-wide injury prevention program (van der Horst, Smits, Petersen, Goedhart, & Backx, 2015), arguments may well be raised that individuals who do not benefit from an injury prevention program are better allowed to fully focus on their performance within the limited time they have available for training. As such, a need for screening risk of injury to inform prevention initiatives will most likely continue to exist.

Screening of movement is based on the premise that if someone systematically moves in a way that is (likely) associated to greater loads on their system, then this individual will be at greater risk of injury. The evidence base to support such screening comes from prospectively identified risk factors that should at least have been verified in independent studies before introducing them in screening as part of preventative measures (Donnelly et al., 2012; van Mechelen et al., 1992). So in order for screening to effectively identify individuals with at risk behaviours, risk factors should be identified and validated carefully through appropriate prospective designs. Three research steps have been proposed to develop and validate a screening program (Bahr, 2016); *step one* is to identify the risk factors and define the cut off value that separates those injured from the uninjured through a prospective cohort study. Through this exploratory study, after undergoing several tasks, individuals will be observed for injuries through a period of time and predictive variables are identified, *step two* would be to validate and repeat the protocol using the previously found predictive variables and predetermined cut-off values in several independent cohorts. *Step three* is to test the effectiveness of the screening program by conducting a randomized control trial to test the effect of combined screening and intervention programs. This aligns with Stages 5 and 6 in Donnelly et al. (2012)'s injury prevention framework. If successful, ACL injuries should be predictable though this identification and validation of risk factors is a costly process. Even if there is a common perception with practitioners that ACL injury risk has been investigated extensively and that a vast amount of knowledge has been generated, this type of evidence remains very limited. It warrants in the first place a critical examination of what exactly is known, and certainly a continued need for validation of existing and/or identification of new risk factors.

Even though it seems like a lot of effort has been put into preventing ACL injury, there is still scarcity of prospective studies on ACL injury risk, especially observing both sexes, across different dynamic tasks and with multi-planar observations. After new risk factors are identified through prospective studies, risk factors are traditionally used independently in screening protocols with little consideration of their relevance across tasks. An issue with the existing evidence is that it always pertains to the risk as identified from single task observation. Traditionally, risk has predominately been tested in a uni-variate way (Beynnon et al., 2015). Similarly, biomechanical risk has been evaluated for 0-dimensional observations, i.e. observations reduced to a discrete value, made in a single task. This may well be a shortcoming as through screening one intends to make a prediction about injury risk based on an individual's generic ability to perform sporting tasks safely. This would require a multi-variate approach in which to consider the predictive strength of multiple observations combined, such as in Bittencourt et al. (2016). The observation of an individual across tasks has not received much attention, mostly because some evidence has revealed that certain observations do not translate well across tasks (Kristianslund & Krosshaug, 2013). However, observing individuals across multiple tasks to see whether they consistently rank at-risk with respect to their peers could in fact reveal more about that individual's neuromuscular strategies than any observation made in a singular task alone. A study by Nigg, Baltich, Hoerzer, and Enders (2015) proposed that an individual's movement may depend on their 'preferred movement path'. The paradigm describes that different conditions or pertubations (in this case type of shoes and/or insoles) can be implemented to the individual but, their preferred movement path may stay the same. This could also perhaps be influenced by the individual's neuromuscular strategies where different pertubations or changes made to the condition, there could be certain muscles that funtions in the same way to the condition regardless of the manipulation. Therefore, this shows that perhaps there is some kind of movement pattern or behaviours that we could observe to identify undesirable movements and if this could be implemented in injury screening, it could maybe provide us with a better indication of whom might be at risk.

## 2.6 Conclusion

Many studies have investigated lower limb biomechanics in the context of non-contact ACL injury risk but the quality of the evidence is unclear. A review and quality assessment of existing biomechanical studies would provide this. Also, further prospective evidence concerning biomechanical risk factors would be welcome for a field of research where there appears to be a mismatch between the perceived risk factors and evidence-informed risk factors. There was also a contrast noticed between the level of complexity of injury mechanisms against the level of complexity of the observed risk factors. Considerable evidence suggests that the ACL injury is multi-planar, whilst most observations to reveal risk factors have been limited to uni-planar variables to represent loads (e.g. abduction moment) or movement patterns (e.g. knee flexion angle). This indicates a need to investigate whether the observation of multi-planar variables could identify more predictive risk factors. In fact, observing both sexes in different dynamic tasks seems necessary if one wishes to obtain a stronger understanding of risk. Finally, evidence supporting biomechanical risk factors has consistently been gathered from observations in a single task only. If risk factors were to be tested in more than one task, and certain individuals would consistently rank at-risk across multiple dynamic tasks, then a task-invariant screening for non-contact ACL injury risk could have considerably increased predictive strength over a single-task observation.

## 2.7 Aims and Objectives

### 2.7.1 Aim

The overall aim of this thesis was to critically evaluate the biomechanical risk factors for non-contact anterior cruciate ligament (ACL) injury during dynamic sporting activities and to explore some novel approaches to evaluating risk as part of screening.

### 2.7.2 Objectives

i. To systematically review the in vivo biomechanical literature that has identified risk factors for non-contact ACL injury during dynamic sports tasks and to critically evaluate the research trends from retrospective and associative studies investigating non-contact ACL injury risk (Chapter 3).

ii. To conduct a two-year prospective cohort study to determine biomechanical risk factors for ACL injury (Chapter 4).

iii. To critically evaluate if existing prospective ACL injury risk factors rank individuals consistently across different dynamic tasks (Chapter 5).

iv. To determine if mechanism-informed multi-planar variables rank individuals more consistently across tasks than uni-planar variables (Chapter 6).

# CHAPTER 3

## Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors

*This systematic review revealed only one prospective study that had determined in vivo ACL biomechanical risk factors, and conflicting evidence was seen within the retrospective and associative studies. When published in Clinical Biomechanics, 2016, these conclusions sparked interest from eminent researchers in the field (Hewett & Myer) and provided an opportunity for us to provide further comment on these results.*

## 3.0 Abstract

Whilst many studies measure large numbers of biomechanical parameters and associate these to anterior cruciate ligament injury risk, they cannot be considered as anterior cruciate ligament injury risk factors without evidence from prospective studies. A review was conducted to systematically assess the in vivo biomechanical literature to identify biomechanical risk factors for non-contact anterior cruciate ligament injury during dynamic sports tasks; and to critically evaluate the research trends from retrospective and associative studies investigating non-contact anterior cruciate ligament injury risk. An electronic literature search was undertaken on studies examining in vivo biomechanical risk factors associated with non-contact anterior cruciate ligament injury. The relevant studies were assessed by classification; level 1 — a prospective cohort study, level 2 — a retrospective study or level 3 — an associative study. An initial search revealed 812 studies but this was reduced to 1 level 1 evidence study, 20 level 2 evidence studies and 175 level 3 evidence studies that met all inclusion criteria. Level 1 evidence showed that the knee abduction angle, knee abduction moment and ground reaction force were biomechanical risk factors. Nine level 2 studies and eighty-three level 3 studies used these to assess risk factors in their study. Inconsistencies in results and methods were observed in level 2 and 3 studies. There is a lack of high quality, prospective level 1 evidence related to biomechanical risk factors for non-contact anterior cruciate ligament injury. More prospective cohort studies are required to determine risk factors and provide improved prognostic capability.

## 3.1 Introduction

Over the last decade, a large number of studies have used in vivo biomechanical methods to investigate links between specific biomechanical parameters and risk of non-contact ACL injury. One advantage being that these parameters have been shown to be modifiable (Hewett, Myer, Ford, & Slauterbeck, 2007). Typically observed parameters include whole body kinematics, lower limb joint moments, and knee and hip kinematics at key events e.g. impact. Understanding the biomechanics of the dynamic movement is crucial in investigating the risk factor of non-contact ACL injury. Biomechanical risk factors have been proposed in all three planes but inconsistency in methods and techniques of evaluating risk factors however have not been examined in detail. Two-dimensional (2D) kinematic video recording (Holden, Colin, Wang, Doherty, & Delahunt, 2014; McLean, Walker, Ford, et al., 2005) has also been used to inform the injury mechanism, but its accuracy and precision are still uncertain. A recent review (Hughes, 2014) implicated a number of biomechanical “risk factors” such as reduced lateral trunk flexion and knee flexion angle, yet it would seem that such measures have only been associated to ACL injury risk and cannot therefore be considered as ACL injury risk factors per se. Risk factors are predictive parameters established from prospective cohort studies, where the parameters showed meaningful differences between ACL injured athletes compared to uninjured athletes. It is perhaps therefore a misconception that there are a large number of established biomechanical risk factors for non-contact ACL injury.

Once risk factors have been established from prospective cohort studies they may be further supported by evidence from retrospective studies which can identify differences between ACL injured and controls, and further understood through associative studies by investigating what can influence risk factors, e.g. approach speed influences knee abduction moments (Vanrenterghem, Venables, Pataky, & Robinson, 2012). As outlined in the ‘Translating Research into Injury Prevention Framework’ (Finch, 2006), these types of studies are needed to strengthen the development of intervention and prevention programs as the success of these programs is underpinned by a solid understanding of the risks associated with sustaining the injury as opposed to any surrogate or any indirect measure of injury. Retrospective studies therefore provide weaker evidence relating to the identification of risk factors than prospective cohort studies, and associative studies build on the evidence rather than generating it. As the field of research progresses, it is desirable that the number of independent studies with a high level of evidence increases (Samuelsson et al., 2013). The research trends relating to the biomechanical risk factors of non-contact ACL injury are unknown and therefore critical examination of the existing evidence is required.

The aims of this study are firstly, to systematically review the in vivo biomechanical literature that has identified risk factors for non-contact ACL injury during dynamic sports tasks and secondly, to critically evaluate the research trends from retrospective and associative studies investigating non-contact ACL injury risk. Risk factors and studies relating to either sex are considered for completeness.

## 3.2 Methods

The Cochrane Handbook (Higgins & Green, 2009) and the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) (Liberati et al., 2009) guidelines were used in conducting this systematic review. Seven authors were involved in the systematic review.

### 3.2.1 Electronic literature search

A systematic electronic database search of PubMed, SCOPUS, Web of Science, CINAHL and SPORTDiscus was conducted for studies between January 1990 and 10th August 2015. The search terms were constructed and tested prior to the initial search for their appropriateness. Search terms were divided into five groups (Table 3.1) and when searching the groups were connected with AND. Depending on the search database, the appropriate search term notation technique was applied.

Table 3.1 Electronic database literature search strategy for key terms used

| Step | Strategy | PubMed | Scopus | Web of Science | CINAHL | SPORTDiscus |
|---|---|---|---|---|---|---|
| #1 | Search "ACL injur*" OR "anterior cruciate ligament injur*" | 2,413 | 3,861 | 7,483 | 4,599 | 1,974 |
| #2 | Search knee OR hip OR ankle OR trunk OR torso OR valgus OR varus OR abduction OR adduction OR flexion OR extension OR "ground reaction force*" OR "internal rotation" OR "external rotation" | 485,043 | 659,671 | 1,364,572 | 99,867 | 67,865 |
| #3 | Search #1 AND #2 | 2,111 | 3,351 | 6,260 | 3,129 | 1,435 |
| #4 | Search biomechanic* OR kinematic* OR kinetic* OR angle* OR moment* OR load* OR torque* OR sagittal OR frontal OR transverse | 985,113 | 3,336,664 | 4,912,796 | 83,466 | 83,973 |
| #5 | Search #3 AND #4 | 1,025 | 1,506 | 1,441 | 1,180 | 765 |
| #6 | Search risk OR prevent* OR predict* OR screening OR associate* OR sensitivity OR specificity OR reproducibility OR reliability OR validity | 7,380,702 | 9,622,122 | 21,467,428 | 1,206,876 | 209,644 |
| #7 | Search #5 AND #6 | 776 | 940 | 969 | 649 | 561 |
| #8 | Search side* OR cut* OR hop* OR land* OR jump* OR sprint* OR run* | 894,257 | 2,867,571 | 4,688,133 | 121,429 | 184,408 |
| #9 | Search #7 AND #8 | 348 | 520 | 590 | 336 | 399 |

### 3.2.2 Study selection

EndNote® (version X7.0.1, Thomson Reuters) was used to select titles and abstracts based on the inclusion and exclusion criteria; and prospective cohort studies, retrospective studies and associative studies were classified as level 1, 2 and 3 evidence, respectively (Table 3.2). Any duplicates found were excluded. A prognostic article was included if the study (i) measured biomechanical variables (e.g. kinetic, kinematic); (ii) measured other variables (e.g. neuromuscular or physiological variables) but still contained biomechanical assessments; (iii) contained risk factors or associations with non-contact ACL injury; (iv) was published in English; (v) involved participants of dynamic sports i.e. those involving rapid dynamic movements such as sudden stops, changes of direction, jump landings, pivoting and side cutting (e.g. basketball, football, hockey, volleyball, handball); (vi) was an in vivo study. Articles were excluded if (i) no abstract was available; (ii) they were a review, systematic review, technical note or meta-analysis; (iii) the study focused on the effect of treatment or training; (iv) their sole focus was on ACL deficient or reconstructed populations; (vi) they were in vitro studies, (vii) there was a non-dynamic sport setting.

Table 3.2 Classification of studies (Level of evidence)

| Level of Evidence | Prognostic Studies—Investigating the Effect of a Patient Characteristic on the Outcome of Disease |
|---|---|
| Level 1 | *Prospective Cohort Study*<br>Observe a large number of uninjured athletes and then monitor their injury status over a period of time. Those athletes that become injured can then be compared to the uninjured group in an attempt to identify differences with a predictive value commonly called risk factors. |
| Level 2 | *Retrospective Study*<br>A study design that takes a look back at the effect of an event that occurred in the past and typically makes comparisons to a control group. In a typical retrospective ACL study, investigators would compare ACL injured or reconstructed athletes to an uninjured control group. |
| Level 3 | *Associative Study*<br>Provides a lower level of evidence because these cannot measure risk factors directly and so instead associates other variables with known risk factors. They can help to understand how known risk factors are influenced by other variables that have not yet been shown prospectively as risk factors themselves. |

Initially, title and abstract selection was completed by authors 2 and 6 independently, in order to avoid risk of bias in identifying potentially relevant papers for full review. If there were discrepancies between the two reviewers, there were discussions between the two to reach a consensus. If consensus could not be reached, the article was referred to author 1 or 7. Next, the full text assessment was reviewed by authors 1 and 7 and if there were any disagreements between the two reviewers, consensus was again sought through discussions between themselves, and a moderator if needed (author 6). Study classifications and the inclusion / exclusion criteria were implemented within this process.

### 3.2.3 Assessment of the risk of bias

Risk of bias assessment was undertaken for level 1 evidence studies (Table 3.3). The Risk of Bias Tool for Cohort Studies by the Cochrane Bias Methods Group was used to review the selected articles. The retrospective and associative studies were not quality assessed as these studies were retrieved only to map current trends of the field. Authors 1 and 7 assessed the risk of bias independently and then reached a consensus. For each item answered 'Yes', one point was given other responses scored 0 points. The total score of the methodological quality ranged between 0 – 9 for the prospective cohort study. If an item was not present, not reported or insufficient information was given, no points were given. An item might not be applicable to a study, so these items were excluded from calculation for quality assessment. Scoring 'Yes' shows that the study has a low risk of bias and 'No' means that the study has a high risk of bias.

Table 3.3 Methodological quality assessment (Risk of bias assessment)

| Description scores | Hewett et al. (2005) |
|---|---|
| a. Was selection of the prospective cohorts drawn from the same population | Y |
| b. Can we be confident in the assessment of activity exposure in subjects | Y |
| c. Can we be confident that any injury was not present at start of the study (prospective) or had suffered from ACL injury and controls had not (case-control)? | Y |
| d. Were the cases (those who acquired ACL injury) appropriately selected? | Y |
| e. Were the controls appropriately selected? | N/A |
| f. Did the study match injured and uninjured subjects (prospective) or cases and controls (case-control) for all variables that are associated with the potential risk factor or did the statistical analysis adjust for these prognostic variables? | N |
| g. Was the nature/cause of the ACL injury well defined? | Y |
| h. Can we be confident in the assessment of the ACL injury? | Y |
| i. Was the follow up of cohorts adequate? | Y |
| Total score | 7/8 |

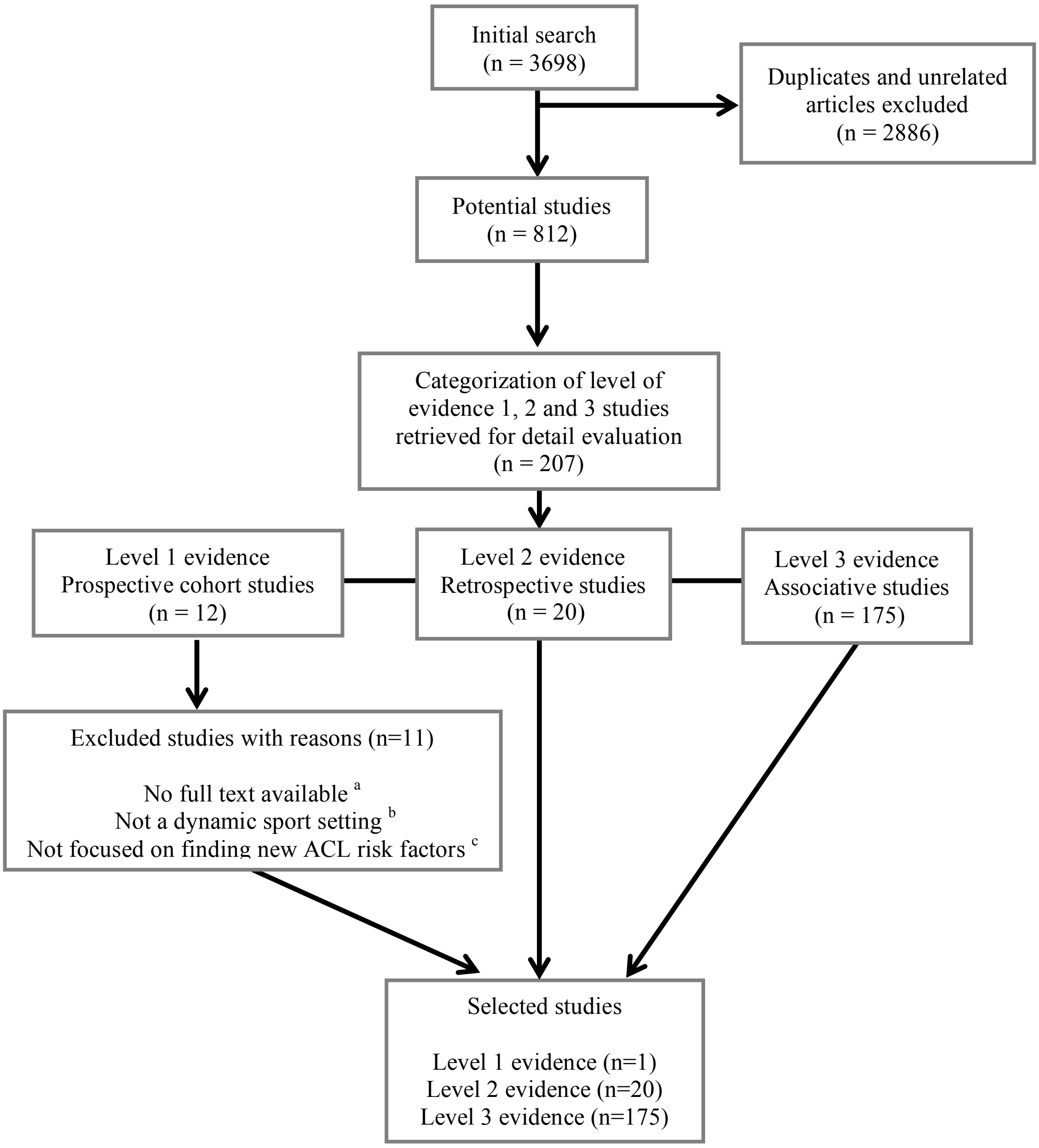
** N/A not applicable, N no or insufficient information, Y yes*

## 3.3 Results

### 3.3.1 Search results

A total of 3698 studies were identified (Figure 3.1) with the database breakdown as follows: PubMed (348), Scopus (520), Web of Science (590), CINAHL (336) and SPORTDiscus (399). When duplicates and unrelated articles (2886) were removed 812 studies remained. After careful screening of titles, abstracts and classification of level of evidence 605 studies were excluded as they did not meet the inclusion criteria and 207 studies remained and underwent full evaluation. Twelve prospective cohort studies were selected for full text assessment of the inclusion and exclusion criteria. A total of 20 retrospective and 175 associative studies were also identified.

Full text assessment of the 12 prospective cohort studies meant that eleven further studies were excluded for the following reasons: (1) one had no full text available (Kimura et al., 2011), (2) one did not meet the requirement of participation in dynamic sports (Liederbach et al., 2008), and (3) nine did not focus specifically on investigating or finding new ACL injury risk factors as they were observing other injuries (e.g. patellofemoral pain syndrome) (Boling et al., 2009; Myer et al., 2015), gender differences (Ford et al., 2010), perfecting screening tools (Myer et al., 2010; Padua et al., 2015; Smith et al., 2012), effect of maturation or joint laxity effects (Hewett et al., 2015; Myer et al., 2008; Soderman et al., 2001). Hence, only one level 1 evidence study (Hewett et al., 2005) was quality assessed.




[a] *Kimura et al. (2011);* [b] *Liederbach, Dilgen, and Rose (2008);* [c] *Boling et al. (2009); (Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010; Hewett, Myer, Kiefer, & Ford, 2015; Myer et al., 2015; Myer, Ford, Khoury, Succop, & Hewett, 2010; Myer, Ford, Paterno, Nick, & Hewett, 2008; D. A. Padua et al., 2015; Smith et al., 2012; Soderman,*

Figure 3.1 Flow diagram of search strategy

### 3.3.2 Level 1 evidence

The selected level 1 evidence study (Hewett et al., 2005) scored 7/8 points in the risk of bias assessment (Table 3.3) hence, this study has a low risk of bias and key information has been summarized. This study was an exploratory prospective study as the authors did not know which variables might predict ACL injury. They observed 9 ACL injuries in a sample of 205 female adolescent basketball, volleyball and football players (14-18 years). The bilateral drop vertical jump (BDVJ) was used to examine landing biomechanics during the first contact phase. A range of biomechanical variables were measured and they found that the group that subsequently had an ACL injury had higher knee abduction angles (KAA) at landing (9° vs. 1.4°), higher peak knee abduction moments (pKAM, -45.3 vs. -18.4 Nm) and higher vertical ground reaction forces (pVGRF) (1266 vs. 1057 N) which distinguished them from the uninjured group. The pKAM predicted ACL injury status with 73% specificity and 78% sensitivity.

### 3.3.3 Level 2 evidence

Of the 20 retrospective level 2 evidence studies (Table 3.4), 14 compared an ACL reconstruction (ACLR) group and 6 compared an ACL deficient (ACLD) group to either a healthy control group or to the individual's uninjured side. Nine studies observed the variables pKAM or KAA to assess ACL injury based on the risk factors found by Hewett et al.. An increased KAA was found both in ACLR (B. M. Goerger et al., 2015; K. M. Stearns & C. D. Pollard, 2013) and ACLD (Hewett, Lynch, et al., 2010) group during side cutting and BDVJ, compared to control groups.

Concerning sex differences, KAA was seen to be higher in females compared to males in both injured and uninjured leg (Yamazaki, Muneta, Ju, & Sekiya, 2010). However, other studies observed no significant difference in KAA when comparing ACLD (Houck, Duncan, & De Haven, 2005a) and ACLR (Lee, Chow, & Tillman, 2014b; Ortiz et al., 2008) individuals compared to controls. While comparing female subjects to male subjects, Miranda et al. (2013b) observed the amount of KAA found in their study did not seem to resemble to a valgus collapse position. Only one study (Ortiz, Olson, Trudelle-Jackson, Rosario, & Venegas, 2011) observed a greater pKAM in an ACLR group during a side hop (6.96 vs. 1.16 N·m/KgBW) and a lower pKAM during crossover hopping (1.31 vs. 5.59 N·m/KgBW) compared to a healthy control group.

The other eleven studies investigated biomechanical variables in the context of stability and postural control (F. Mohammadi et al., 2012; Oberlander, Bruggemann, Hoher, & Karamanidis, 2012; F. T. Sheehan, W. H. Sipprell, 3rd, & B. P. Boden, 2012; K. A. Webster & Gribble, 2010b), gait (von Porat, Henriksson, Holmstrom, et al., 2006), vision (Bjornaraa & Di Fabio, 2011), limb asymmetry (Holsgaard-Larsen, Jensen, Mortensen, & Aagaard, 2014), walk and jog patterns (Chmielewski, Rudolph, Fitzgerald, Axe, & Snyder-Mackler, 2001a), gender differences (Paterno et al., 2011), as well as neuromuscular aspects (Vairo et al., 2008b). Landing strategies and medio-lateral control of ACLD and ACLR patients were also investigated by P. E. Roos, K. Button, V. Sparkes, and R. W. van Deursen (2014) and found that these groups had not fully recovered.

ACLD and ACLR subjects showed significantly poorer clinical and biomechanical results compared to controls (Chmielewski et al., 2001a; Oberlander et al., 2012; Paterno et al., 2011). However, no differences were found in knee joint kinematics and kinetics during gait (von Porat, Henriksson, Holmstrom, et al., 2006). Distinguishing characteristics of ACLD groups included posterior centre of mass (COM) changes (F. T. Sheehan et al., 2012), increased time to stabilization (K. A. Webster & Gribble, 2010b), postural sway and other unique adaptations aimed at stabilizing the knee (Vairo et al., 2008b). Distinguishing characteristics of ACLR groups included greater postural sway (F. Mohammadi et al., 2012) and altered responses to visual disruption (Bjornaraa & Di Fabio, 2011).

### 3.3.4 Level 3 evidence

A total of 175 associative studies were retrieved from the search. We identified that 57% of these associative studies involved both sexes a further 30% investigated females only with only 11% of studies investigating males. The remaining 2% was unknown as it was not specified in the abstract or the full text. Only 19% of the papers studied adolescent athletes (between 10 – 18 years old) while the rest of the studies included adults. Out of the 175 associative studies, 30 studies used pKAM and KAA to assess non-contact ACL injury risk, all of which were published after Hewett et al.'s prospective study (Hewett et al., 2005) which included athletes aged ranging between 14 to 17 years old. There are a wide variety of other biomechanical factors assessed in level 3 studies including the association of risk factors with sex, maturational development, sport type, fatigue, task and neuromuscular aspects.

Studies have shown that females tend to have a greater risk of getting an ACL injury (Agel et al., 2005; Hewett et al., 2005). This is supported by the findings found in the associative studies where females are more likely to have poorer landing technique such as reduced hip and knee flexion at initial contact (Baker, 2009; Beutler, de la Motte, Marshall, Padua, & Boden, 2009); higher knee abduction (Hughes, Watkins, & Owen, 2008; M. F. Joseph et al., 2011) and less knee flexion throughout landing (Beutler et al., 2009) compared to males. Landing with a more erect posture and greater angular velocities than males has also been speculated to contribute to non-contact ACL injury in females (Decker et al., 2003).

Vertical jump tasks have been combined with the influence of fatigue (Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013; Cortes, Greska, Kollock, & Onate, 2011; Iguchi, Tateuchi, Taniguchi, & Ichihashi, 2014; Sanna & O'Connor, 2008; Tsai, Sigward, Pollard, Fletcher, & Powers, 2009) to examine the effect on biomechanical variables. Around 13% of the associative studies examined the effect of fatigue on ACL injury risk factors. Fatigue has been observed to alter both the movement patterns and motor control (Benjaminse et al., 2008; Cortes et al., 2013; Cortes et al., 2011). Both males and females demonstrated reduced KAA moving closer to neutral and decreased knee flexion at initial contact after fatiguing (Benjaminse et al., 2008; Cortes et al., 2013). In addition, the pKAM at peak stance and hip flexion angle was also decreased and a larger pVGRF was seen in females after fatigue (Cortes et al., 2013; Iguchi et al., 2014). Knee and hip control also altered neuromuscular characteristics (Gehring, Melnyk, & Gollhofer, 2009; Thomas, McLean, & Palmieri-Smith, 2010).

Over a third (36%) of the level 3 studies observed cutting manoeuvres with the majority being anticipated rather than unanticipated tasks. The inclusion of unanticipated tasks increases the magnitude of joint loads and increases the KAA in females compared to males (Baker, 2009; Ford, Myer, Toms, & Hewett, 2005; Houck, Duncan, & De Haven, 2006; Jamison, McNally, Schmitt, & Chaudhari, 2013; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007a, 2007b). Muscular activity imbalance and reduced hip flexion angles have also been associated with non-contact ACL injury (Brown, Palmieri-Smith, & McLean, 2009; Landry et al., 2007b).

A filterable summary of the selected level 3 evidence papers research trend can be found in the supplementary material (Appendix A).

Table 3.4 Summary of the selected level 2 evidence papers

| Subject Condition | Author | Characteristics of subjects | Methodology of Data Collection / Task | Biomechanical Outcome Measure | Results/Findings |
|---|---|---|---|---|---|
| ACLR | Bjornaraa and Di Fabio (2011) | ACLR; 17F<br>healthy controls; 17F | Vision – used electromagnetic sensor | Absolute knee displacement, Peak and average absolute knee velocities, time to peak ground reaction force (pGRF) (% of cut). | - ACLR: < knee displacement, velocity, ↑ time to reach pGRF relative to healthy subjects' non-dominant knee.<br>- Visual disruption: some effect on movements. |
| | Benjamin M. Goerger et al. (2015) | ACLR-injured (ACLR-INJ); 8M, 4F<br>ACLR-uninjured (ACLR-UNINJ); 9M, 10F<br>healthy controls, 20M, 19F | DVJ | KAA, Knee adduction angle, Hip abduction angle, Hip adduction angle, Knee internal rotation angle, Knee extension moment, Hip flexion moment, Anterior tibial shear force | - ACL injury & ACLR altered lower extremity biomechanics<br>- ACLR-INJ & ACLR-UNINJ: ↑ hip adduction and KAA.<br>- ACLR- INJ: ↓ anterior tibial shear force, knee extension moment & hip flexion moment.<br>- Control group: No high-risk biomechanical changes observed |
| | Holsgaard-Larsen et al. (2014) | ACLR; 23M<br>healthy controls; 25M | Counter movement jump (CMJ), one-leg hop for distance | Sagittal knee moment, Sagittal range of motion (RoM), Knee joint angle at transition point, Jump height, Asymmetry ratio | - Both types of CMJ: Between-limb asymmetry ratios for RoM differed between ACLR and controls<br>- Jump for distance: ACLR > jump length asymmetry |
| | Lee, Chow, and Tillman (2014a) | ACLR; 3M, 8F<br>healthy controls; 3M, 8F | Side-step cutting manoeuvre; with 3 pre-cutting approach (counter movement, one step and running) | Knee flexion angle, Knee extension angle, KAA, Knee adduction angle, Internal and external rotation angles, Peak joint moments | - ACLR: > knee internal rotator moment<br>- Inter-group comparisons; ACLR > abductor and internal rotator moments only in the running condition<br>- ACLR: at ↑ risk of re-injury when participating in high-demand physical activities. |
| | Miranda et al. (2013a) | ACL intact ($ACL_{INT}$); 5M, 5F<br>ACLR; 4M, 6F | Jump cut manoeuvre. | GRF, Knee flexion, Knee extension, KAA, Knee adduction, Tibial internal - external rotation, Anterior - posterior knee translation, Medial - lateral knee translation, Anterior – posterior knee translation excursions, Medial – lateral knee translation excursions | - F: < knee flexion angle excursion during a jumpcut manoeuvre resulting in a ↑ pGRF & ↑ rate of anterior tibial translation.<br>- ACLR: < GRF in jump cut manoeuvre than $ACL_{INT}$<br>- ↑ landing stiffness leads to ↑ rate of anterior tibial translation while performing a jump-cut manoeuvre. |
| | Farshid Mohammadi et al. (2012) | ACLR; 22M, 8F<br>healthy controls; 24M, 6F | Single-leg stance & single leg drop jump. | Centre of pressure (CoP) anteroposterior amplitude and velocity, CoP mediolateral amplitude and velocity, Vertical GRF, Loading rate | - ACLR: > postural sway in operated leg compared with the non-operated side and matched limb of the control group<br>- ACLR: > pGRF and loading rate on the uninvolved limb compared to control group at landing |

| | | | | |
|---|---|---|---|---|
| | | | | - Static & dynamic postural measures have high test–retest reliability, ranging from 0.73 to 0.88. |
| Oberländer, Brüggemann, Höher, and Karamanidis (2012) | ACLR; 12<br>healthy controls; 13 | Single leg hop. | Margin of stability, CoM, GRF, Ankle dorsiflexion moments, Ankle plantarflexion moments, Knee flexion moments, Knee extension moments, Hip flexion / extension moments, Pendulum length, Trunk angle | - ACLD leg: < external knee flexion moments, > moments at the ankle & hip compared to controls<br>- ACLD leg: joint moment redistribution > anterior position of the GRF vector, which affected the moment arms of the GRF acting about the joints<br>- ACLD leg: trunk angle > flexed over the entire landing phase compared to controls<br>- Significant correlation found between moment arms at the knee joint and trunk angle |
| Ortiz et al. (2008) | ACLR; 13F<br>healthy controls; 15F | Single leg drop jump, up-down hop task.<br>Electromyography (EMG). | GRF, Hip flexion, Hip adduction, Hip internal rotation, Knee flexion, KAA, Knee external rotation, Knee extension moments, KAM, Anterior-posterior shear forces | - No differences between groups: peak hip & knee joint angles for the drop jump task.<br>- ACLR: significant differences in neuromuscular activity & anterior-posterior knee shear compared with controls in drop jump task.<br>- No differences between groups: for peak hip & knee joint angles, peak joint kinetics, or EMG during up-down hop task. |
| Ortiz et al. (2011) | ACLR; 13F<br>healthy controls; 15F | Side to side hopping task.<br>EMG. | Hip flexion, Hip adduction, Knee flexion, KAA, Knee extension moments, KAM | - Controls & ACLR: similar hip & knee-joint angles during both types of hopping.<br>- > Hip-joint angles: crossover hopping in both groups, & knee-joint angles did not differ between the groups or hops.<br>- Knee-joint moments: group X manoeuvre interaction.<br>- Control group: > knee extension & valgus moments during crossover hopping<br>- ACL: > KAM during side hopping |
| Paterno et al. (2011) | ACLR; 21M, 5F<br>healthy controls; 13M, 29F | DVJ. | GRF | - After ACLR, M & F: at the time of return to sport demonstrated involved limb asymmetries in pGRF during landing from a bipedal task.<br>- DVJ landing phase: significant side-by-group interaction for pGRF in the entire cohort.<br>- ACLR involved limb: < Vertical GRF than the uninvolved & both the preferred limb & nonpreferred limb in the control group<br>- No effect of sex was noted. |

| | | | | | |
|---|---|---|---|---|---|
| | P. E. Roos, K. Button, V. Sparkes, and R. W. M. van Deursen (2014) | ACLD; 18M, 3F<br>ACLR; 19M, 4F<br>healthy controls; 11M, 9F | Single leg hop. | GRF, CoM velocity, Knee extensor moment, knee RoM, Knee flexion angle, Hop moment, Ankle moment, CoM angle | - ACLD: smallest hop distance<br>- Control: largest hop distance<br>- ACLR: used similar kinematic strategy to controls, but had a reduced peak knee extensor moment.<br>- ACLD & ACLR: Fluency reduced |
| | Kristen M. Stearns and Christine D. Pollard (2013) | ACLR; 12F<br>healthy controls; 12F | Sidestep cutting manoeuvre. | KAA, KAM, Knee adductor moment, GRF | - ACLR: ↑ average KAA & peak knee adductor moments compared to controls. |
| | Vairo et al. (2008a) | ACLR; 5M, 9F<br>healthy controls; 5M, 9F | Single leg drop jump. Neuromuscular, biomechanical & isokinetic strength & endurance evaluations. | GRF, Hip & net summated extensor moments, Hip joint flexion, Knee joint flexion, Ankle joint flexion | - No significant differences in hip & net summated extensor moments within or between groups.<br>- ISGA (ipsilateral semitendinosus and gracilis autograft) ACLR: ↓ pGRF at landing for involved limb compared to uninvolved & controls, > peak hip joint flexion angles at landing for involved compared to uninvolved limb & controls at initial ground contact, ↑ peak hip joint flexion angles at landing for involved limb compared to uninvolved & pGRF, > peak knee & ankle joint flexion angles when landing on involved limb compared to control at pGRF. |
| | K. A. Webster and Gribble (2010a) | ACLR; 12F<br>healthy; 12F | Single leg hop. | Resultant vector of time to stabilization, GRF | - ACLR: longer time to stabilize than control |
| ACLD | Chmielewski, Rudolph, Fitzgerald, Axe, and Snyder-Mackler (2001b) | ACLD; 9M, 2F<br>healthy controls; 8M, 2F | Walking & jogging | Knee flexion angle, Internal knee extension moment, Support moment (at peak knee flexion), GRF | - ACLD: flexed involved knee < than healthy subjects & uninvolved side during walking.<br>- ACLD: < GRF during loading response, < knee support moment, & ↑ ankle support moment during walking compared to controls. In jogging, involved knee angle at initial contact > extended compared to controls, & < knee flexion than uninvolved side.<br>- No differences in kinetics during jogging. |

| | | | | |
|---|---|---|---|---|
| Hewett, Lynch, et al. (2010) | ACLD; 2F, twins healthy controls; 72F | Jump distance, DVJ single leg hop. | KAA, Knee flexion angle, Side to side asymmetries, Anatomic & anthropometric: Femoral notch width height, weight, BMI, Side to side asymmetries, Vertical jump height | - ↑ KAA at one knee in both of the twins relative to uninjured controls at initial contact & at max displacement during landing.<br>- ACL-INJ twin: ↓ peak knee flexion motion at both knees than controls during landing. |
| Houck, Duncan, and De Haven (2005b) | ACLD; 10M, 5F healthy controls; 7M, 7F | Straight-ahead task, crossover-cutting task, & a sidestep-cutting task. | Knee flexion angle, KAA, Knee internal rotation, Hip flexion angle, Hip abduction angle, Hip internal rotation, KAM, Knee flexion moment, Knee internal rotation moment, Hip abduction moment, Hip flexion moment, Hip internal rotation moment, Stride length | - ACLD noncoper: 1.8° to 5.7° < knee flexion angle compared to control across tasks, used 22% to 27% < knee extensor moment during weight acceptance compared to control, 34% to 39% > sagittal plane hip extensor moments compared to control, hip frontal & transverse plane moments differ from the controls |
| F. T. Sheehan, W. H. Sipprell, and B. P. Boden (2012) | Movie captures of 20 athletes;<br>Movie captures of 20 athletes performing a similar manoeuvre that did not result in injury (controls) | 1-legged landing manoeuvre that resulted in an ACL injury | CoM_BoS/femur, Limb angle (relative to the gravity vector), Trunk angle (relative to the gravity vector | - Landing with the CoM far posterior to the BoS may be a risk factor for noncontact ACL injury.<br>- ACLD land with CoM far posterior to the BoS. |
| von Porat, Henriksson, Holmström, et al. (2006) | ACLD; 12M healthy controls; 12M | Gait, step activity & cross over hop. | GRF, Step length, Velocity, Stance phase, Peak knee flexion, Knee power absorption, Knee extensor moment, Knee power generation | - ACLD after 16 years < knee extension strength<br>- No difference in knee joint kinematics & kinetics<br>- ACL-INJ: < knee extension strength was associated with joint moment reductions during step activity & cross over hop.<br>- No significant differences in knee joint kinetics & kinematics in an ACL injured group 16 years after injury compared with a matched control group. |
| Yamazaki, Muneta, Ju, and Sekiya (2009) | ACLD; 32M, 31F healthy controls; 14M, 12F | Single leg squat. | Relative angles between the body, thigh, & lower leg using an electromagnetic device:<br>Knee flexion, Knee adduction, Knee external rotation, Hip flexion, Hip adduction, Hip external rotation, KAA | - UNINJ leg of ACL-INJ M: < external knee rotation than M control dominant leg<br>- UNINJ leg of ACL-INJ F: > external hip rotation & knee flexion & less hip flexion than F control dominant leg<br>- M INJ leg: < external knee & hip rotation, less knee flexion, & > knee varus than UNINJ leg.<br>- F INJ leg: > knee varus than UNINJ leg. |

| | | |
|---|---|---|
| | | - F > external hip rotation & knee valgus than M did in both the INJ & UNINJ legs. |

*ACL = Anterior cruciate ligament*
*ACLD = Anterior cruciate ligament deficient/injured*
*ACLR = Anterior cruciate ligament reconstructed*
*INJ = Injured*
*UNINJ = Uninjured*
*BoS = Base of support*
*M = Males*
*F = Females*
*GRF = Ground reaction force*
*pGRF = Peak ground reaction force*
*KAM = Knee abduction moment*
*KAA = Knee abduction angle*
*RoM = Range of motion*
*CoM = Centre of mass*
*DVJ = Drop vertical jump*
*EMG = Electromyography*
*$ACL_{INT}$ = Anterior cruciate ligament intact*
*↑ = increased , ↓ = decreased*

## 3.4 Discussions

This study reviewed the level of evidence with respect to the in vivo biomechanical literature to identify risk factors for non-contact ACL injury during dynamic sports tasks, and it critically evaluated research trends from retrospective and associative studies around non-contact ACL injury risk. The key findings of this review were a lack of level 1 evidence and a large number of level 3 evidence studies.

Ideally, associative studies are designed from a strong base of level 1 and level 2 evidence. Having observed only one level 1 evidence study and conflicting level 2 evidence, this appears not to be the case. A similarly skewed evolution of studies has also been observed in the more mature field of ACL reconstruction research (Samuelsson et al., 2013) where studies with a lower level of evidence were published at a greater rate than level 1 or 2 evidence studies. Our study observed a large number of level 3 evidence studies that associated other variables to KAA and pKAM. An important consequence of this is parameter bias, which is where only a limited number of parameters are used to inform retrospective or associative study designs. This was observed to some extent in the retrospective studies and to a greater extent in the associative studies. Parameter bias makes the results of these studies dependent on the reproducibility of the level 1 evidence and to our knowledge the findings of Hewett et al. (2005) have as of yet not been confirmed independently. As long as that is the case, care should be taken using the KAA and pKAM parameters only.

### 3.4.1 Recent level 1 evidence

Abstracts from two additional prospective-cohort studies were presented at the IOC 2014 World Conference Prevention of Injury & Illness in Sport, Monaco, France. The first study (Kristianslund, 2014) collected prospective bilateral drop vertical jump task (BDVJ) data from 708 Norwegian elite female football and handball players and observed 38 non-contact ACL injuries from a bilateral drop vertical jump task. This has recently been published (Krosshaug et al., 2016) with 42 non-contact ACL injuries registered and neither pKAM, KAA, knee flexion angle and pVGRF predicted ACL injury. The second study involved US military cadets (Padua, 2014) also using a bilateral drop vertical jump task, observed 117 ACL injuries in males and females from a cohort of 5758 cadets. They also found that pKAM and KAA did not predict ACL injury but they did observe increased hip adduction and increased internal tibial rotation at contact in those who sustained an ACL injury. Both studies sampled larger cohorts and observed considerably more ACL injuries yet found that neither KAA nor pKAM predicted ACL injury. This has important consequences for the large number of level 3 associative studies examining pKAM and KAA only. The effect of parameter bias in this field therefore has important consequences for these studies and highlights the importance of having well-established level 1 evidence before conducting associative work. In the situation where conflicting level 1-evidence exists, it is clear that further prospective studies should be prioritized to develop a critical mass of biomechanical variables that predict ACL injury across studies. Researchers may wish to consider relevant factors identified from associative studies that may affect ACL injury risk yet have not been prospectively assessed including more dynamic tasks such as sidestepping, the influence of fatigue, and unanticipated movements.

#### 3.4.2 Extrapolation and standardization

Appropriate caution should be taken when extrapolating the results of level 1 evidence studies to retrospective and associative studies. Specifically altered KAA, pKAM and pVGRF have only been found to predict ACL injury when calculated within the experimental protocol and sample of Hewett et al. (2005). Although this study is highly cited (1031 citations at time of submission), their low number of ACL injuries observed, and lack of familywise-error correction, means results require independent confirmation. The use of the KAA and pKAM was observed in many studies involving different age-groups, demographics, males and other tasks such as single leg landings and sidestepping. Although in many cases, significant effects on the KAA and pKAM have been found it is recommended that level 1 evidence studies inform their predictive value of ACL injury.

Many conflicting results were found in both level 2 and 3 evidence studies. This is likely due to the variety of tested samples e.g. males, females, ACLD, ACLR, pre and post-puberty, ages, the variety of tasks e.g. BDVJ, side cutting, hopping, single leg landings. Whilst samples may be difficult to standardize given that most recruitment is governed by convenience, the choice of task and biomechanical methods, which can significantly affect the KAA and pKAM (Kristianslund, Krosshaug, Mok, McLean, & van den Bogert, 2014; Kristianslund, Krosshaug, & van den Bogert, 2012; Myer, Khoury, Succop, & Hewett, 2013; Robinson, Donnelly, Tsao, & Vanrenterghem, 2014; Robinson & Vanrenterghem, 2012), could be standardized. The BDVJ task is frequently chosen as it replicates the task from the prospective evidence (Hewett et al., 2005). It has the advantage that it is simple and reliable although its credibility as an ACL-injuring manoeuvre has been questioned (Kristianslund & Krosshaug, 2013). Furthermore, the BDVJ does not replicate sport specific landings, which are commonly only supported on one leg (Kristianslund & Krosshaug, 2013; Morgan, Donnelly, & Reinbolt, 2014). The use of a more sport-specific movement as a measurement tool may produce more sensitive and specific ACL injury predictors. One interesting observation was that a large number of studies used non-prospectively assessed tasks to associate to prospectively identified variables. Side cutting or sidestepping in particular was widely used (36%). The use of tasks that are informed by prospective evidence should be considered. Other than the task's used, Hewett et al. only filtered their force data, this could have an important influence on their interpretation of the peak knee abduction moments as artefacts are introduced during the inverse dynamics process if cut-off frequencies are not matched between the forces and marker data (Kristianslund et al., 2012). Hewett et al. (2012) responded to this criticism citing that this evidence was from a different task (a run-cut) and questioning the timing of the artefacts introduced, but nonetheless this introduction of artefacts into the data remains. Hewett et al. also presented their ground reaction forces without normalisation which means that between-subject variations in weight were not accounted for. Furthermore, they also used a very simple biomechanical model where reflective markers are only placed on joints and one on each thigh and no functional hip and knee calibration was used to calculate the knee joint axis or hip joint centre. Though a study by Besier et al. (2003) has found that the functional hip and knee to be reliable and a way of reducing soft tissue artefacts. While miss-locating of the hip joint centre can propagate error and cause kinematic delays (Stagni et al., 2000)."This type of model would not typically be used to evaluate dynamic tasks because of the concern for the influence of soft tissue artefact on the results. This may therefore have consequences for the interpretation of the biomechanical measurements. Given all of the above points raised with respect to the work of Hewett et al. (2005) studies confirmation / replicating these results are warranted.

### 3.4.3 Barriers to strengthen the available evidence

Prospective studies are known to be expensive, time consuming and challenging with the possibilities of dropouts and negative results. The challenges of such studies have been outlined in detail (Padua, 2010). In particular, biomechanical techniques such as three-dimensional motion capture and analysis tend to be time consuming; often requiring ~ 2 hours per study participant for data capture. This is obviously inhibitive to testing large cohorts. These challenges could be mitigated through automated data capture and analysis software and routines, efforts to move towards multi-centre studies through conducting inter-laboratory reliability assessments and standardization of methods, including using the same biomechanical models and data processing techniques that could increase numbers of participants and observed injuries whilst reducing methodological inconsistency. One recently published attempt to standardize biomechanical analyses across three laboratories showed promising results (DiCesare et al., 2015). Once methodological standardization is established and the number of prospective studies increase, a meta-analysis of prospective studies will provide additional means by which risk factors can be evaluated.

Samuelsson et al. (2013) identified a trend that high level of evidence studies in ACL reconstruction research (including randomized controlled trials) increased over time. This trend has not been observed in the context of the biomechanical contributors to primary non-contact ACL injury risk. Although, with the publication of new prospective abstracts (Kristianslund, 2014; Padua, 2014) and a large new prospective cohort study (Krosshaug et al., 2016) more high level of evidence studies are being conducted which is welcome. Yet, additional research efforts are needed. The lack of high level evidence may also be because this research is preventative rather than therapeutic which typically means that the direct benefit to individuals is less clear and hence financial resources are less readily available. In addition, evidence from a cost-effectiveness study (Swart et al., 2014) shows that prevention programs give a better outcome where it reduces ACL injury incidence from 3% to 1.1% per season and are lower in cost to conduct.

### 3.4.4 Limitations

We specifically chose to focus on in vivo biomechanical studies. Whilst we acknowledge that other biomechanical research paradigms have made significant contributions to the understanding of ACL injury biomechanics including *in vitro* and *in silico* studies, it was our intention to focus on risk factors in vivo using participants of dynamic sports as these are most likely to inform injury prevention practice.

## 3.5 Conclusions

Our search revealed one prospective cohort study which aimed to determine how in vivo biomechanics can serve as a predictor of non-contact ACL injury. This study found that female athletes with increased dynamic knee abduction angle and with a high knee abduction moment are risk factors for ACL injury, albeit in a small sample of injuries. Many associative studies are based on these results alone and are therefore at risk of task and parameter bias. Though a reasonably large number of level 2 and 3 evidence studies are available, more prospective cohort studies are needed to drive on-going work with the purpose of developing prevention programs and clinical interventions. Generating a critical mass of high quality level 1 evidence should therefore be the priority for research to advance the understanding of in vivo biomechanical risk factors for non-contact ACL injury.

# CHAPTER 4

## A prospective study for biomechanical ACL injury risk factors (2014 – 2016)

*In this chapter, the outcomes of a two-year prospective cohort study are presented as well as a transition to a contingency plan as no ACL injuries were observed*

## 4.0 Abstract

As conflicting findings and lack of high quality prospective evidence assessing the biomechanical risk factors of ACL injury, there is high demand for additional information. Therefore, additional prospective evidence is needed to confirm these risk factors independently. The aim of this study was to determine the biomechanical risk factors for non-contact ACL injury during dynamic sporting activities in a two-year prospective cohort study. One-hundred and four healthy athletes who were free from lower-limb injuries for at least 12 months and who regularly participating in dynamic sports took part in this study. Five trials of bilateral drop vertical jumps (BDVJ), single-leg hops (SLHOP), single-leg drop vertical jumps (SLDVJ) and sidestep (SS) tasks were performed. Participant's activity and injury exposure were monitored for one-season through a bespoke mobile phone application. Eleven participants had no LKIS mobile application registered and were excluded from the prospective study. Out of 93 participants, 51% of the participants finished the monitoring requirement of 36 weeks. Though 14% of the participants only managed to comply for 0 to 4 weeks. No ACL injury was observed during the monitoring period. As insufficient ACL injuries were observed, no new biomechanical risk factors for ACL injury could be identified.

## 4.1 Introduction

In order to reduce the occurrence of ACL injuries, the injury mechanism and risk factors for injury should be understood (Section 2.2). Some prospective studies have assessed the risk factors associated with ACL injury (Goetschius et al., 2012; Hewett et al., 2005; Myklebust et al., 2003) but there is a high demand for additional information, as the findings are conflicting and their results are based on; (i) a small number of injuries, (ii) a restricted set of subject cohorts (not multi-sport), (iii) non-comparable assessment methods (different measuring tools) and (iv) only on one sex (females) or athlete's status (either elite or recreational). These may explain why there are conflicting risk factors identified (Kristianslund & Krosshaug, 2013) and might explain why existing injury prevention programs show mixed results (Donnelly et al., 2012).

Chapter 3 (Section 2.5) showed the importance of prospective studies and that there is a lack of high-quality prospective biomechanical data relating to ACL injuries. At the time that this study commenced (September 2014) only the prospective study of Hewett et al. (2005) was available. Their findings that knee abduction angles and knee abduction moments in bilateral drop vertical jump task are predictors of ACL injury among female athletes have been very influential and have directed and influenced the last 13 years of ACL injury research. Additional prospective evidence is needed to confirm these risk factors independently.
The aim of this study was to determine the biomechanical risk factors for non-contact ACL injury during dynamic sporting activities in a two-year prospective cohort study. The findings of this study could also lead to the development of new screening tools for risk of ACL injury and be used to improve existing knee injury risk screening practice.

## 4.2 Methods

### 4.2.1 Participants

The aim of this study was to recruit as many participants as possible (female and male) between the age of 18 – 35 years old. Participants who were free from lower limb injuries for at least 12 months and who regularly participated at least twice a week in highly dynamic sports such as football, handball, field hockey, basketball and netball were eligible to participate i.e. recreational/amateur athletes, beginner or university athletes etc…

### 4.2.2 Experimental Design

The prospective cohort study was known as the Liverpool Knee Injury Study (LKIS). Informed consent was obtained prior to testing. The Liverpool John Moores University Ethics

Committee approved the study. Prior to testing, participants were given a Sports and Injury History questionnaire (Appendix B), Exercise Readiness Questionnaire (Appendix C) and a consent form (Appendix D).

### 4.2.3 Dynamic Tasks

Participants were required to attend the biomechanics research laboratory once for a two-hour session. On the day of the testing, participants were required to do a warm-up which included light jogging and dynamic stretching. Participants were required to perform a series of dynamic tasks, which were randomly sequenced. After 10 minutes of dynamic warm-up and familiarisation, each participant was randomly assigned to perform bilateral drop vertical jumps, single-leg drop vertical jumps, single-leg hops and 45° sidesteps on both their dominant and non-dominant legs. As a recent study by van Melick et al. (2017) has shown that the leg used to kick a ball had 100% agreement between the self-reported and observed dominant leg for both men and women; prior to testing, participants were asked which leg they preferred to use to kick a ball in order to determine their leg dominance. Each task was performed five times and participants were given practice trials to ensure that they were sufficiently familiarised before completing each dynamic task.

*Bilateral and single-leg drop vertical jump*

A bilateral drop vertical jump (BDVJ) and single-leg drop vertical jump (SLDVJ) were performed maximally from a 30cm high box following the protocol described in a previous study (Myer, Ford, Khoury, Succop, & Hewett, 2011). The BDVJ task was chosen to replicate what previous prospective studies' have used (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017). Participants were instructed to stand on the box with the feet positioned 35cm apart. Before jumping off, participants were instructed to step off with one leg, landing with both legs at the same time in the middle of each of the force platform and to immediately perform a maximal vertical jump (aiming for maximum height) using both arms (Figure 4.1). For the single-leg drop vertical jump (SLDVJ) before jumping off, participants were instructed to stand on the box with one leg and the other leg remained off the ground, then to hop off with one leg and once landed in the middle of the force platform, to immediately do a maximal vertical jump single-legged while raising both arms up in the air (Figure 4.2). The first landing was examined as this was where 'initial contact' and 'take off' was taken from. Trials were not considered suitable when any of the instructions were not followed i.e. did not immediately do a vertical jump or they landed too far off the force platform. Such trials were discarded). Both dominant and non-dominant leg was examined for BDVJ and SLDVJ.

Figure 4.1 Sequence of the bilateral drop vertical jump task

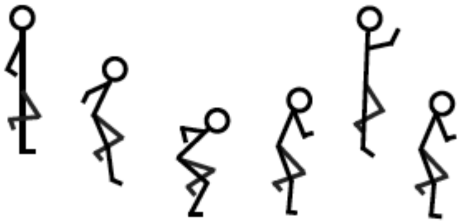


Figure 4.2 Sequence of the single-leg drop vertical jump task

*Single-leg hop (SLHOP)*

A SLHOP was performed by jumping forward onto a force platform from a distance equal to the participant's leg length (i.e. greater trochanter to lateral malleolus) (K. E. Webster, Gonzalez-Adrio, & Feller, 2004). The SLHOP task was included to replicate a deceleration stopping manoeuvre, which is commonly associated with injury. Participants were instructed to stand on one leg from the starting point and jump forward to the centre of the force platform on the same leg while still keeping the other leg off the ground. Only a firm landing with no movement or wobble and a single contact on the force platform was counted as a successful hop. Both dominant and non-dominant leg was examined for SLHOP.

*Sidestepping manoeuver (SS)*

In an ideal scenario, unanticipated SS was preferred as it is considered to better represent an accurate dynamic sporting conditions (J. H. Kim et al., 2014; Meinerz, Malloy, Geiser, & Kipp, 2015) but time constraints of the test session meant this was simply not possible. Therefore an anticipated SS was chosen for this study where the manoeuvers were performed by cutting sideways 45$^{o}$ on the force platform after a 10 m straight run (Figure 4.3). Timing gates (Brower Timing System, Utah, USA) placed 2 m apart with the second timing gate 50 cm away from the force platform were used to monitor the approach speed. Participants were instructed to do a straight run and when they reach the force plate, to immediately do a cut (either to the right or left), following through the poles. To limit inter-trial variability, this task was deemed successful when the approach speed was between 4 to 5 m.s$^{-1}$ as it was found to be a safe balance between task achievement and loading, any approach speed beyond this will be discarded. Alongside that, the foot landed entirely on the force platform (Vanrenterghem et al., 2012) and the participant ran through two narrow vertical poles positioned just off the force platform at the desired cut angle was accounted for a succesfull trial. Both dominant and non-dominant leg was examined for SS.

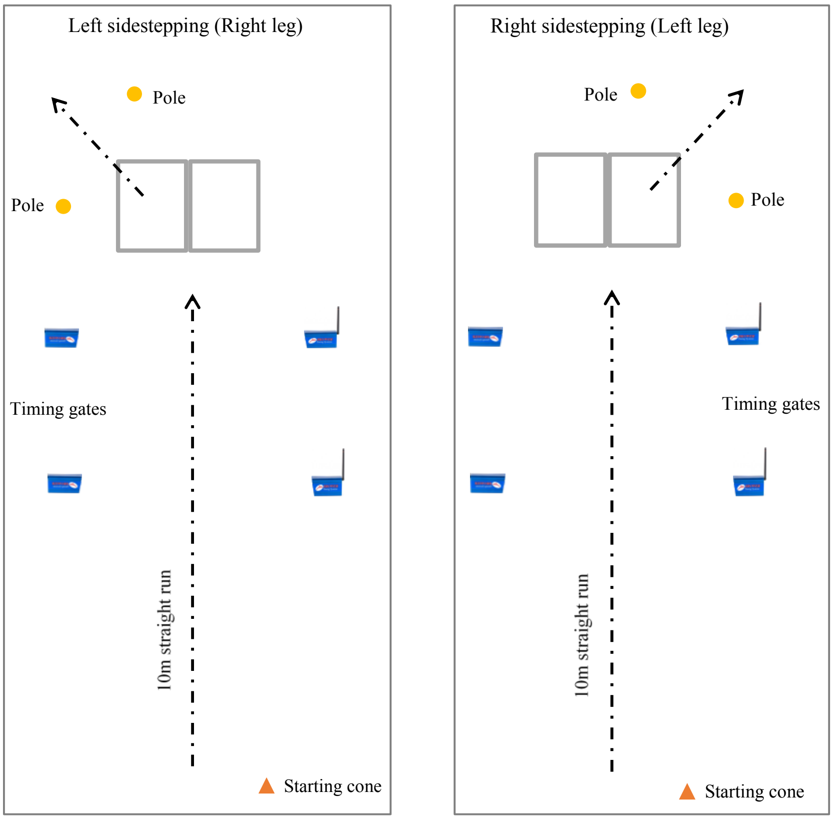



Figure 4.3 Sidestepping data collection set-up

### 4.2.4 Project Automation Framework (PAF) integration

Tracking each and every single participant and analysing the data can be time consuming. Therefore, to help manage data collection and initial processing, a PAF was used to assist in speeding up the workflow. A PAF was used in the Qualisys Track Manager (QTM) to customized data collection setup that automated repetitive workflow while streamlining the motion capture process for each participant. A custom made Visual3D analysis pipeline was created and the PAF called Visual 3D from within QTM to automate the model building and analysis. The automated project workflow simplifies the report generation whilst making it quicker and easier to produce a finished report from a click of a button (Figure 4.4).

In order to collect quality data efficiently and speed up the data collection process, a PAF was created with for all the motion capture needed i.e. Automatic Identification of Markers (AIM), volume calibration, static calibration, functional knee calibration, functional hip calibration, bilateral drop vertical jump, single-legged drop vertical jump, single-leg hop and sidecutting. By having these pre-set, time is saved from manually naming and saving each trials. After data collection is completed, the data could straight away be processed by clicking the analyse button. With PAF, the data process takes less than 3 minutes to complete where manually the data processing (from marker labelling)  could take up to 2 -3 hours per participant.

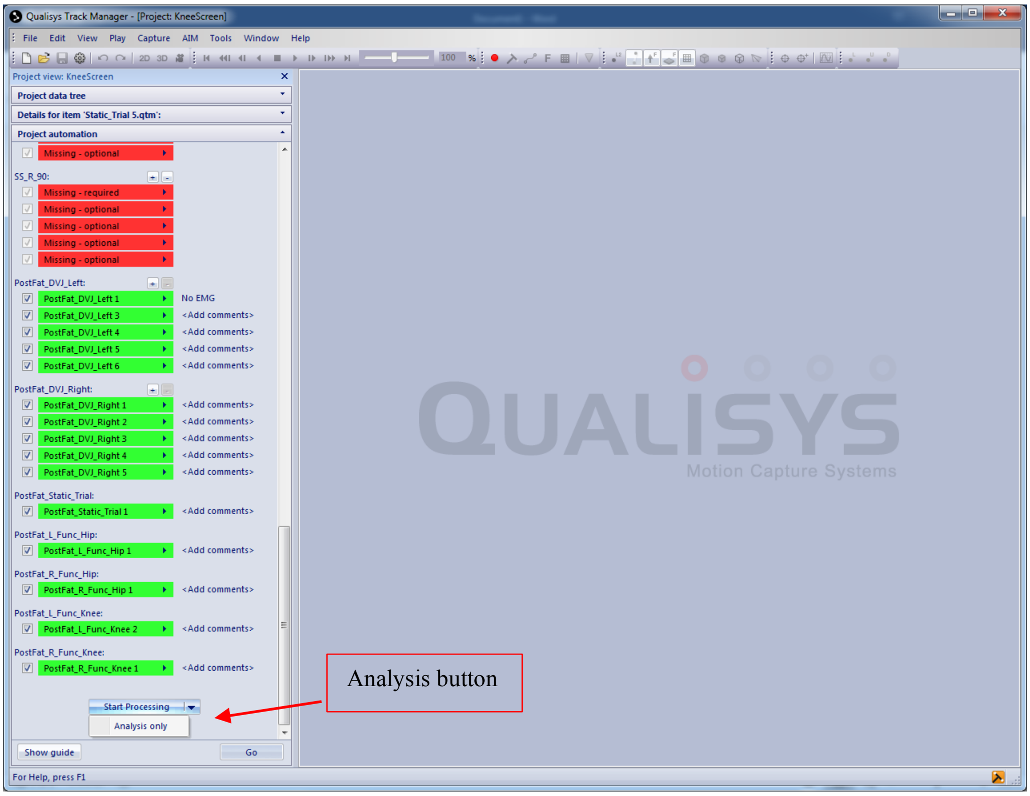



Figure 4.4 Screenshot of the PAF integration in the Qualisys Track Manager software

### 4.2.5 Injury and Exposure Monitoring

A one-season follow-up was conducted. In order to ease the follow-up procedure, a mobile phone application (iOS and Android) was created to monitor participant’s activity and injury exposure. The mobile application was developed with the assistance of Liverpool John Moores University’s staff, Dr Chelsea Dobbins and Dr Martin Hanneghan from the School of

Computer Sciences. The researcher, colleague and the researcher’s supervisory team designed all aspects of the mobile application and layout (Figure 4.5).

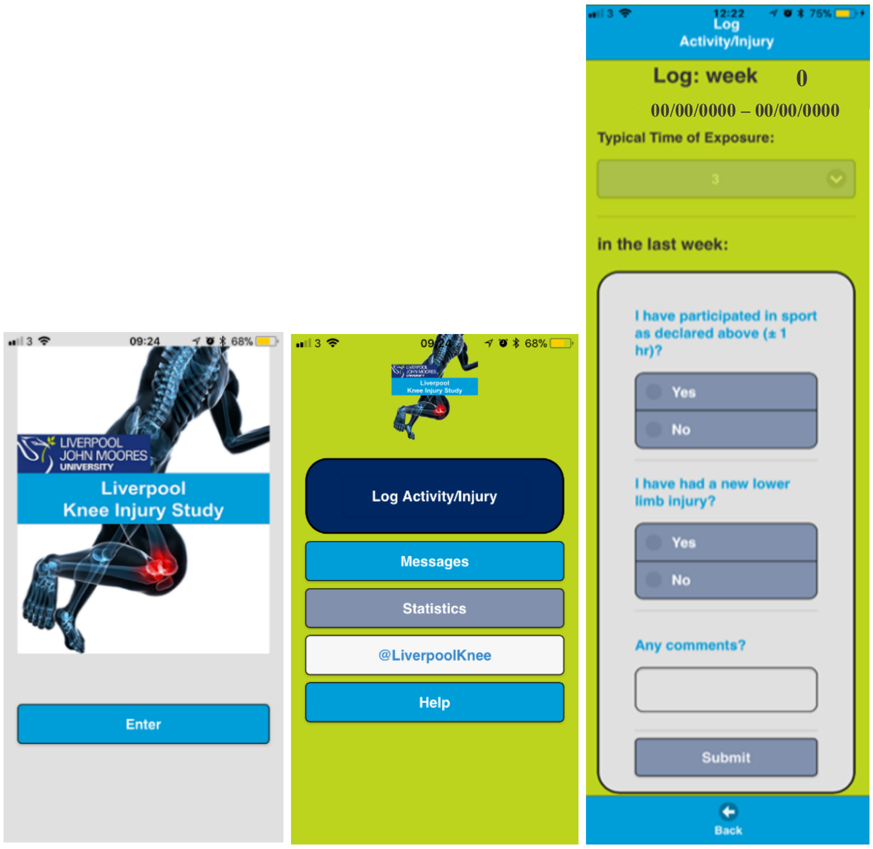



Figure 4.5 (Left to right) LKIS mobile application welcome page, menu page and log activity / injury page

Participants were granted access to the mobile app at the end of the testing session. Participants’ anticipated time of exposure was declared upon installation of the LKIS mobile application. Data concerning sports exposure and dynamic-loading-related injuries were collected weekly and at the time of exposure and verified with individual players if necessary through an online injury registration system. On a weekly basis participants were notified by the app to respond to two primary questions concerning their declared sporting exposure and current injury status in the form of a simple yes/no response to the questions; (i) *I have participated in sport as declared above (± 1 hour)*, and (ii) *I have had a lower limb injury*. During the monitoring period, follow-up questionnaires (Appendix E,F,G,H) were administered if the participant’s sport participation changed or they declared an injury (Figure 4.6).


Figure 4.6 A flow chart describing the follow-up process and questionnaires completed when relevant.

The mobile application sent notifications to the participants for 36 weeks (1 season). If participants missed the first notification, another alert for the week was sent automatically the next day. The incoming data from the mobile application was stored in an allocated web server and checked weekly by the researcher (Figure 4.7). For participants who did not own a smart phone, the injury monitoring procedure was conducted through email.

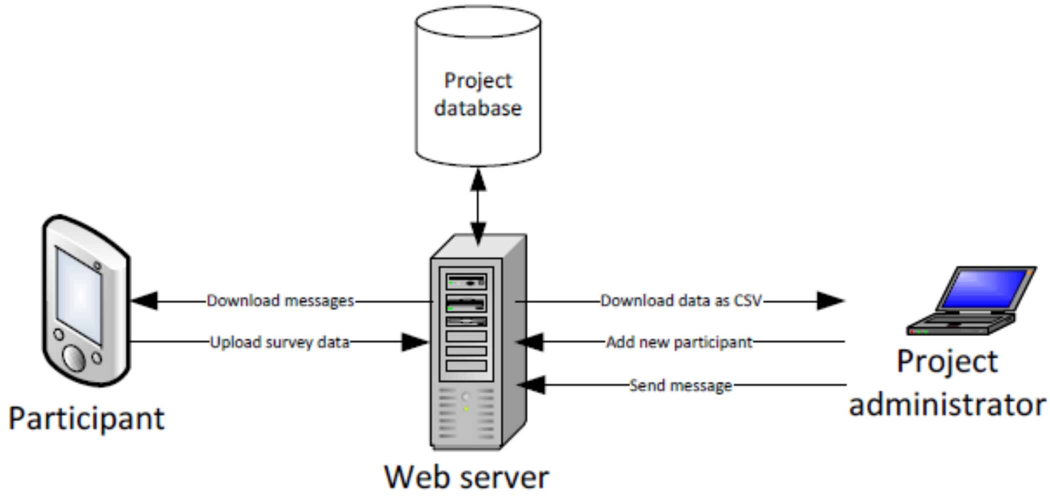



Figure 4.7 The system composed of two distinct entities – the LKIS mobile application and a web server administration interface. The collected questionnaire was stored remotely on the web server, where it was available for the researcher to download.

## 4.3 Results

*As no ACL injury observed during the monitoring period, the biomechanical outcomes will be covered in subsequent studies (Chapter 5 and 6).*

Eleven pilot participants had no LKIS mobile application registered therefore they were excluded from this study. Forty-six females (mean ± SD: age, 21.97 ± 3.98 years; height, 170.04 ± 9.85 cm; mass, 69.92 ± 12.15 kg) and forty-seven males (mean ± SD: age, 21.83 ± 3.91 years; height, 170.24 ± 9.69 cm; mass, 69.94 ± 12.13 kg) participated in the study. Participants were involved in highly-dynamic sports such as football (n=38), netball (n=11), field hockey (n=10), basketball (n=9), rugby (n=7), handball (n=6), volleyball (n=6), badminton (n=4), squash (n=1), tennis (n=1). The participant compliance in reporting their activities and injury through the LKIS mobile application is illustrated in Figure 4.8. Out of 93 participants, 51% of the participants finished the monitoring requirement of 36 weeks. Though 14% of the participants only managed to comply for 0 to 4 weeks.

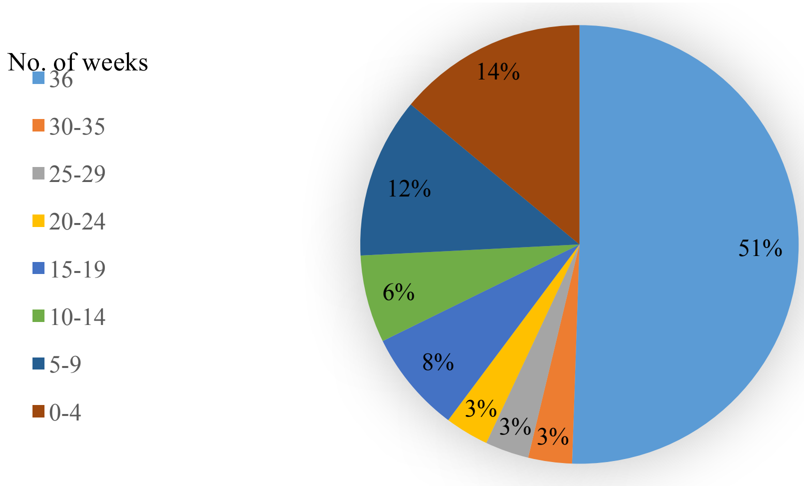



Figure 4.8 Participants compliance through self-reporting LKIS mobile application (n=93)

The highest declared weekly exposure was 20 hours and the lowest was 2. Most of the participants had declared 6 hours of exposure per week while only three participants declared 20 hours (Figure 4.9). During the 36 weeks of follow-up, no ACL injuries were reported, though a few other injuries were seen. Injuries were recorded and verified through the LKIS mobile application log, in the "injury comments" section and also through the Post-injury Questionnaire for the lower limbs (Figure 4.4). Common lower limb injuries reported were hamstring or quadriceps strain/pull (n=7), lateral collateral ligament strain (n=1), ankle sprain (n=4) and muscle/ligament soreness around the foot and knee (n=6).

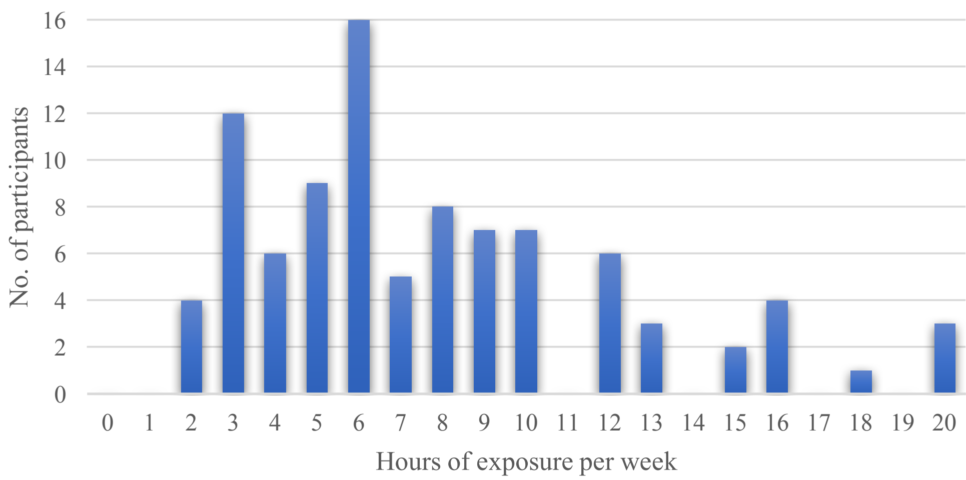



Figure 4.9 Participants' declared exposure on average (per week)

## 4.4 Discussion

As previous prospective study only observed 9 ACL injuries in a sample of 205 participants (Hewett et al., 2005), therefore a bigger sample size was needed to observe bigger number of injuries. As the calculated incidence are 0.17 and 0.23 per 1000 hours for male and female (Agel et al., 2016), in order to observe higher number of injuries, a bigger sample size and longer exposure time was needed. Despite the extensive recruitment effort and outreach, this study only manage to recruit 104 participants. This may be due to several causes, though the problem that mainly effected the recruitment number was due to the university's semester break. As our participants were mainly university athletes, this means that recruitment were only most efficient during term times.

Unfortunately, this study did not observe any ACL injuries. The 93 participants in this study was monitored based on self-declared exposure which adds up to 26,064 hours of exposure over the full testing period. Typical ACL injury incidence rates are 0.10 (females) and 0.057 (males) per 1000 hours of athlete exposure during active sport participation (Bjordal et al., 1997). With the above incidence rates, monitoring males and females and this study's total hours of exposure, we might have expected to see at the very least one or two injuries in our cohort. According to a more recent study (Agel et al., 2016) with incidence rates of 0.17 and 0.23 per 1000 hours for male and females respectively, we might have expected to observe at least 4 to 5 injuries, which would approach the number of injuries in a previously reported study (Hewett et al., 2005). Our participants were athletes who participated in high-risk dynamic sports in which ACL injury commonly occur in (Gianotti et al., 2009; Gornitzky et al., 2016; Joseph et al., 2013; Prodromos, Han, Rogowski, Joyce, & Shi, 2007). One characteristics of our cohort is that everyone was aged above 18 years old and injury incidence is higher in younger adolescents (aged 13-18) (Bjordal et al., 1997; Mall et al., 2014) and late childhood (aged 10–12) (Caine, Purcell, & Maffulli, 2014; Gianotti et al., 2009; Shaw & Finch, 2017).

The timing of when the participants were recruited and assigned to the LKIS mobile application may also affect the study's outcome. In a study of injury reporting by short messaging service (SMS) (Ekegren, Gabbe, & Finch, 2014), it was seen that throughout the season the number of injuries dropped. Our participants were recruited at the beginning of their season, they therefore during the monitoring period may have become better adapted to the training and competition's needs of their sports (Braham, Finch, McIntosh, & McCrory, 2004; McManus et al., 2004). As the participants mostly came from the university sports teams, in addition to training sessions they were often also receiving strength and conditioning training perhaps making them less susceptible to injury. The timing of this study was restricted by the availability of students during the academic year as this was the most feasible time for the monitoring to occur.

Many different methods have been used to monitor exposure and injury (Ekegren et al., 2014; Moller, Attermann, Myklebust, & Wedderkopp, 2012; Nilstad, Bahr, & Andersen, 2014) though none had used a bespoke mobile application. Forty-seven participants from this study managed to complete the LKIS monitoring for the whole monitoring period while 13 of the 93 participants completed the monitoring for less than 4 weeks. The LKIS mobile application was developed to lead to a high compliance during follow-up as previous studies had seen increased response rates in novel injury surveillance methods (Ekegren et al., 2014; Moller et al., 2012). However, only 51% of the participants in our study completed the 36 weeks monitoring. This may be due to several possible causes such as changing to a new mobile phone, starting new employment or lack of interest. Some of these causes has also been seen by Hanauer, Wentzell, Laffel, and Laffel (2009) in their study on the Computerized Automated Reminder Diabetes System (CARDS) where they saw a decline in response rates throughout their 3-month study. They also assumed that despite the advance reminder system, over time it became laborious and participants lose interest (Hanauer et al., 2009). This perhaps, may explain some of the causes of our monitoring responses. Although monitoring compliance was mixed, we are confident that no ACL injuries were sustained or remained unreported. In summary, we were confident that the LKIS mobile monitoring application was fit for purpose and it is likely that other reasons such as self-reporting more substantially influenced monitoring success.

A self-reported follow-up system which requires the participant to respond independently means that it is not possible for the researcher to track their actual training and exposure hours throughout the 36 weeks. We therefore acknowledge the limitations that come with this type of monitoring system including a reliance on the integrity of the participants. An extreme solution to this could be hiring research assistants or creating a larger interdisciplinary team to rigidly enforce injury reporting e.g. Padua (2010), or using wearables that track the activity levels of participants.

## 4.5 Conclusion

Overall, as insufficient ACL injuries were observed, no new biomechanical risk factors for ACL injury could be identified. A contingency plan was therefore developed and used for the remainder of this thesis. It focussed on using the data collected from the prospective cohort study to meet the following objectives related to utility of biomechanical risk factors for ACL injury risk screening; the first study wished to determine if established prospective ACL injury risk factors rank individuals consistently across different dynamic tasks (Chapter 5) and the second study was more exploratory, using mechanism-informed risk factors, to determine if multi-planar mechanism-derived variables ranked individuals more consistently across tasks than uni-planar variables (Chapter 6).

# CHAPTER 5

## How consistently do ACL injury risk factors classify an individual across different tasks?

*In this chapter a novel risk profile or "movement signature" is presented. An athlete has a strong movement signature if they have a task-invariant movement pattern leading to a consistently ranked score on a biomechanical risk factor. Almost all participants showed task-invariant movement signatures of which 58 % were undesirable.*

## 5.0 Abstract

Several prospective studies have suggested biomechanical risk factors for non-contact anterior cruciate ligament (ACL) injury however; the relationship of this risk factor alone does not inform task-invariant behaviours. Ideally, risk factors should be ranked consistently across a variety of dynamic tasks and form an individual's task-invariant 'movement signature'. Therefore, this study aims to determine if established prospective ACL injury risk factors rank individuals consistently across multiple bilateral and single-leg dynamic tasks, and to explore if a task-invariant movement signature can frequently be identified for individual athletes. Forty-one female and forty-six male athletes regularly participating in dynamic sports participated in a controlled laboratory study. 5 trials of bilateral drop vertical jumps (BDVJ), single-leg hops (SLHOP), single-leg drop vertical jumps (SLDVJ) and sidestep (SS) tasks were performed. Knee abduction angle at initial contact (KAA), peak knee abduction moment (pKAM), peak knee flexion angle (pKFA), peak vertical ground reaction force (pVGRF) and medial knee displacement (MD) were extracted and correlated between tasks. Each participant was ranked according to each risk factor, and then grouped into quintiles for each task. Rank score and absolute sum of error for each participant were also calculated. Moderate to good correlations were observed between SLDVJ and SLHOP across all risk factors ($\rho$=0.41-0.86). KAA showed moderate to good correlations across tasks ($\rho$ =0.43-0.86) while the remaining variables showed very low to moderate correlations ($\rho$=-0.02-0.69). Individual analysis revealed a high number of movement signatures (140 out of 174 participants leg) and more than half were highly ranked. The results suggests that KAA showed most potential in providing task-invariant information concerning an individual's ACL injury risk. However, correlation analysis alone does not inform us of the individual's relative change across tasks. Further individual analysis proved the existence of task-invariant movement signatures and its capability to identify undesirable movement behaviours.

## 5.1 Introduction

Screening is the core process of detecting individuals who are at risk of a disease or condition. The early identification of people who are “at-risk”, means prevention or treatment programs can be implemented to prevent or reduce future illness or diseases. In the context of injury prevention in sports, the main aim of screening is to identify individuals who are at increased risk and may benefit from a prevention program. In order for screening to effectively identify individuals with at risk behaviours, risk factors should be considered carefully through appropriate prospective study designs (Bahr, 2016). Traditionally, risk factors are only assessed through one observed variable in a single task, whereas one would expect that an individual who is at risk would demonstrate a particular behaviour across different tasks, demonstrating a movement pattern that is task-invariant. If this were true, task-invariant risk factors could form an individual’s “movement signature” – a collection of variables characterising an individuals’ at-risk behaviours across tasks.

In the context of anterior cruciate ligament (ACL) injuries and as discussed in Section 2.3 and 2.4, undesirable movement and loads are problematic in dynamic sports (Alentorn-Geli et al., 2009; Boden et al., 2000; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Krosshaug et al., 2007). Researchers and practitioners therefore use a variety of dynamic tasks to examine ACL injury risk behaviours. These have included vertical drop jumping (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017), single-leg landing and hop tasks, and sidestepping manoeuvers (Boden et al., 2000; Zebis, Andersen, Bencke, Kjaer, & Aagaard, 2009). Findings from Chapter 3 have shown that only a small number of prospective studies have identified biomechanical risk factors of non-contact ACL injury in females. Hewett et al. (2005) found that greater peak knee abduction moment was the strongest predictor of ACL injury when landing in a bilateral drop vertical jump, alongside greater knee abduction angle at initial contact and greater peak vertical ground reaction force. In a similar task, Krosshaug et al. (2016) found only greater medial knee displacement to be a predictor of ACL injury out of five risk factors considered. Another study found that stiff landings (a more extended knee and greater peak ground reaction force) were associated with increased non-contact ACL injury risk (Leppanen, Pasanen, Kujala, et al., 2017). As different risk factors were identified in these prospective studies all of these risk factors will be considered in the present study to determine if any are task-invariant.

Some studies have begun to examine biomechanical risk factors between tasks. A study by Kristianslund and Krosshaug (2013) compared the bilateral drop vertical jump and sport-specific sidestepping task. In their study, the knee abduction moment displayed a poor correlation between two tasks. Other studies (Jones, Herrington, Munro, & Graham-Smith, 2014; McLean, Walker, & van den Bogert, 2005) have however suggested that dynamic valgus was reasonably consistent across single-leg landing tasks, reporting a good correlation in the peak knee abduction angle across tasks and a moderate to good correlation for peak knee abduction moments (Harty, DuPont, Chmielewski, & Mizner, 2011; Jones et al., 2014). However, all of these studies looked for correlational relationships only. For an individual athlete, correlation alone fails to describe how an athlete may change their relative position within a group and whether they are ranked similarly across tasks.

In order for screening to be of value to an individual athlete, considering a threshold behaviour based on a singular observation in a single task is unlikely effective to identify those who are at risk with acceptable sensitivity and specificity at the same time (Bahr, 2016). The neuromechanical *Principle of Individuality* explains how the motor modules may generate individuality in movement patterns (Ting et al., 2015). Therefore, an individual may have their own "motor program styles" which are dependent on their movement history, learning processes and experiences which have developed over many repetitions. For instance, when observing someone walking, most of the time just by observing his or her gait pattern, one can recognise who that person is (Cutting & Kozlowski, 1977). Maybe a similar approach could be applied in injury screening. If characteristics of an individual can be identified across a number of tasks, then these are likely hard-wired behaviours that are task-invariant and representative of an athlete's behaviour, in other words, the athlete's movement signature. Based on the existence of a movement signature, one may predict that critical behaviours would rate consistently with respect to other individuals from an observed cohort. Furthermore, observing the consistency of key characteristics across dynamic tasks may give us a complete insight into the possibility of task-invariant screening for non-contact ACL injury risk for both males and females.

This study aimed to determine if established prospective ACL injury risk factors rank individuals consistently across multiple bilateral and single-leg dynamic tasks, and to explore if a task-invariant movement signature can frequently be identified for individual athletes.

### 5.2.1 Methods

### 5.2.1 Participants and experimental design

After quality checking the biomechanical data, 87 participants were available to be included for this study (17 discounted participants from the 104 prospective study had either bad biomechanical data due to missing markers that were not fixable [5], they were pilot participants who when initially tested did not perform all four dynamic tasks [9] or their biomechanical data has not yet been thoroughly quality checked in time for this study [3]). Forty-one female (mean ± SD: age, 22.2 ± 3.8 years; height, 163.9 ± 7.5 cm; mass, 64.0 ± 10.2 kg) and forty-six male (mean ± SD: age, 21.2 ± 3.4 years; height, 175.5 ± 8.6 cm; mass, 75.0 ± 12.1 kg) athletes who were free of lower limb injuries for at least 12 months participated in this study. Full description of participants and experimental design were described in Section 4.2.1 and 4.2.2.

### 5.2.2 Dynamic Tasks

Participants were required to perform the bilateral drop vertical jump (BDVJ), single-leg drop vertical jump (SLDVJ), single-leg hop (SLHOP) and a 45° sidestepping (SS). Full details of the dynamic tasks involved has been described in Chapter 4 (Section 4.2.3).

### 5.2.3 Biomechanical assessments of the dynamic tasks

Motion data were captured at 250 Hz using ten optoelectronic cameras (Oqus Cameras, Qualisys AB, Gothenburg, Sweden). Ground reaction forces were measured by two force platforms sampling at 1500 Hz (9287C, Kistler Instruments Ltd., Winterthur, Switzerland). Forty-four spherical markers were attached to the participants according to the previously described LJMU Lower Limb and Trunk model (Figure 5.1) (Malfait et al., 2014; Vanrenterghem, Gormley, Robinson, & Lees, 2010). Static and functional joint trials were collected prior to testing to define functional hip and knee joint centres. Participants stood in the anatomical position for the static calibration; this was taken to define the anatomical coordinate systems. The functional knee calibration was conducted by flexing and extending the knee for 5 s whilst the leg was off the ground. The functional knee trial was used to project the lateral and medial knee markers onto the functional knee axis (Besier et al., 2003, Robinson et al., 2012). The functional hip calibration was taken to calculate the hip joint centre and this was conducted in a 15 s trial with 5 s of abduction-adduction, flexion-extension and rotation of the hip. Both the hip joint centre and knee axis were calculated based on the algorithm implemented in Visual 3D (Schwartz et al., 2004). Knee joint moments from both limbs were estimated using inverse dynamics. Motion data were modelled and analysed using Butterworth filter with 20 Hz cut-off frequency in Visual 3D (v.5.02.30 C-Motion, Germantown, MD, USA) as it was deemed to be most appropriate as consistently filtering both forces and motion data may avoid the introduction of artefacts into data (Bisseling & Hof, 2006; Kristianslund et al., 2012).

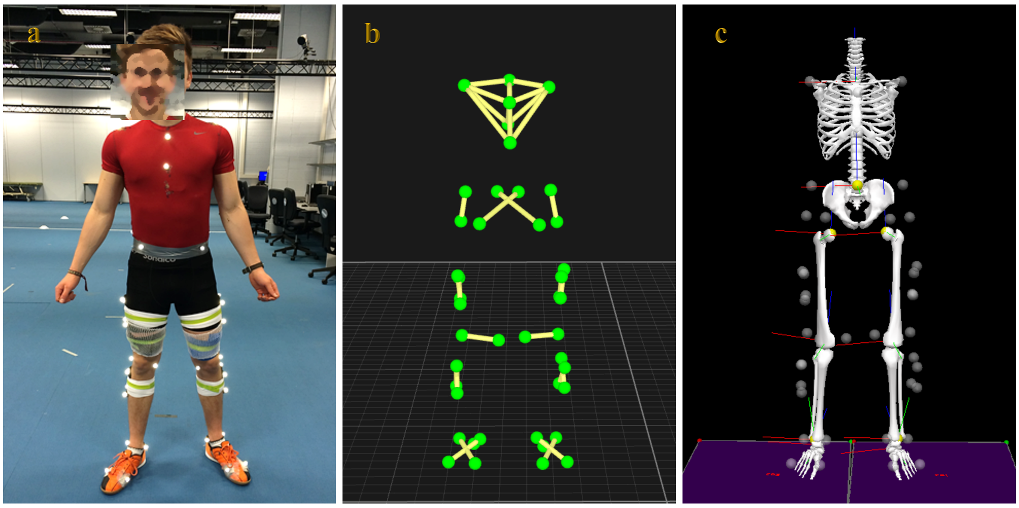



Figure 5.1 LJMU Lower Limb and trunk model (a) marker placement, (b) Qualisys Tracking Manager AIM model and (c) Visual 3D model

Prospectively identified ACL risk factors (Table 5.1) were then calculated (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017). Initial contact was defined as the point where the filtered vertical ground reaction force exceeded 20 N and take-off was defined as the point when the foot comes off the ground as it passes the filtered vertical ground reaction force of 20 N threshold (page xiv). Peak values were obtained within the initial contact and the take-off instances for BDVJ, SLDVJ and SLHOP. Specifically for sidestepping, peak values were taken within the weight acceptance phase (page xv) which is within the initial contact to the end of the passive phase as it was found to be at its maximum magnitude in the sagittal and transverse plane and is often associated with the timing of ACL injury occurrence, which is within 40 milliseconds from initial contact (Besier et al.,2001; Dempsey et al., 2007; Koga et al., 2010). External moments was presented in this study. Angle and moment convention used were as follows; (-) flexion, (+) extension, (-) abduction and (+) adduction. The reliability for key variables has been previously studied (Malfait et al., 2014; Sankey et al., 2015) except for medial knee displacement.

Table 5.1 Biomechanical risk factors from previous prospective studies obtained from bilateral drop vertical jump task

| Variable | Author |
|---|---|
| Knee abduction angle at initial contact | Hewett et al. (2005) |
| Peak knee abduction moment | Hewett et al. (2005) |
| Medial knee displacement | Krosshaug et al. (2016) |
| Peak knee flexion angle | Leppanen, Pasanen, Kujala, et al. (2017) |
| Peak vertical ground reaction force | Leppanen, Pasanen, Kujala, et al. (2017) |

The medial knee displacement was previously described (Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017) and was created using a custom Visual 3D script (v. 5.02.30, C-Motion, Kingston, Canada). The medial knee displacement was defined as the change of medial knee position from touchdown to peak knee abduction (Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017) (Figure 5.2). Medial knee position was the perpendicular distance from the knee joint centre to the line joined by the hip and ankle joint centres projected on the frontal plane. When the knee joint centre was lateral to this line, medial knee position was given a value of zero. Medial knee displacement was not derived for sidestepping as it was not considered appropriate given the abducted position of the hip and extended knee position. Means and standard deviations were calculated for all of the variables.

Figure 5.2 Medial knee position was the perpendicular distance from the knee joint centre to the line joined by the hip and ankle joint centres projected on the frontal plane.

*Permission has been granted to use this image. (Krosshaug et al., 2016)*

### 5.2.4 Statistical Analysis

Statistical analyses were performed using SPSS (23.0.0.2, SPSS Inc., Chicago, Illinois, USA) for both dominant and non-dominant legs. Mean values for each task were obtained and correlated in task pairs using a Spearman's rank correlation coefficient ($\rho$). Correlations were rated as very good (0.90 - 1.00), good (0.70 - 0.89), moderate (0.40 - 0.69), poor (0.20 - 0.39) or very poor (0.00 - 0.19) (Field, 2013). The coefficient of variation was calculated to quantify the group variation (task and leg dominance). Coefficient of variation is the ratio of the standard deviation ($s$) to the mean ($\bar{x}$) expressed as;

$$CV = \frac{s}{\bar{x}} * 100\%$$

For each variable, paired tasks were separated by sex and leg dominance. A paired t-test was used to determine whether there were any significant differences between leg dominance from the same participant. No Bonferroni correction was used in this study.

Each participant group was ranked according to each risk factor, and then grouped into quintiles for each task. The 5$^{th}$ quintile displays the highest score, which represented the worst or more undesirable score, while the 1$^{st}$ quintile represented the lowest scores or more desirable. To keep interpretation of the quintiles the same the pKFA data were reversed to match this interpretation. Quintile ranks were represented with the colour yellow, green, turquoise, dark blue and purple, 1st, 2nd, 3rd, 4th and 5th respectively. The sum of task rankings for each participant and an absolute sum of error was calculated to observe the behaviour of each participant across tasks:

The sum of each task's quintile rank was calculated to observe if participants ranked in the same quintile across tasks e.g. if a participant was ranked in the 1st quintile for all tasks of the variable, their rank score would be 1+1+1+1 = 4 and if a participant ranked 5$^{th}$ in BDVJ, 1$^{st}$ in SLDVJ, 4$^{th}$ in SLHOP and 5$^{th}$ in SS, their rank score would be 5+1+4+5 = 15. For each variable's column, the score was sorted by descending order.

The absolute sum of errors was calculated to describe the extent to which participants' rankings changed between tasks. The absolute sum of errors compared the differences between quintile ranks for each pair of tasks, e.g. if participant ranked 1$^{st}$ for BDVJ, 3$^{rd}$ for SLDVJ, 1$^{st}$ for SLHOP and 2$^{nd}$ for SS for KAA, that would give an absolute error score of 7 (2 [pair BDVJ & SLDVJ] + 0 [pair BDVJ & SLHOP] + 1 [pair BDVJ & SS] + 2 [pair SLDVJ & SLHOP] + 1 [pair SLDVJ & SS] + 1 [SLHOP & SS]). Participants who were in the same quintile rank across tasks for KAA would have an error score a 0 (0+0+0+0+0). A median value of the absolute sum of error score was identified for each variable and annotated with a white line (median-error) (page xiv). The absolute sum of errors was then sorted by ascending order for each variable.

### 5.2.5 Movement signature

A movement signature was defined as a consistent quintile rank across tasks in a particular risk factor where all tasks ranked in the same quintile or 3 tasks ranked in the same quintile, with 1 task ranked ± one difference to the majority quintile i.e. 3$^{rd}$, 3$^{rd}$, 3$^{rd}$, 2$^{nd}$ or 3$^{rd}$, 3$^{rd}$, 3$^{rd}$, 4$^{th}$ (Figure 5.3) (page xiv). When there is inconsistent quintile ranking across tasks, no movement signature is observed.

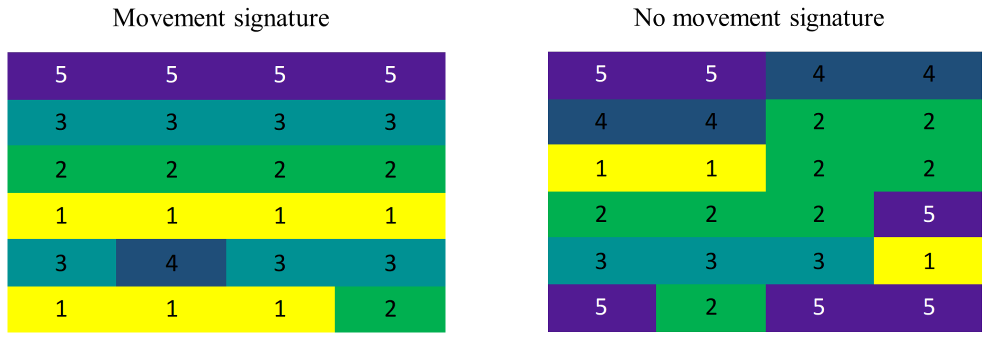



Figure 5.3 An example of quintile ranks across tasks and what constituted a movement signature or no movement signature.

## 5.3 Results

The descriptive data (Table 5.2) displayed that the knee abduction angle (KAA) at initial contact appeared to be generally consistent across tasks for both males and females whereas peak knee flexion angle (pKFA) was quite different across tasks. Peak knee abduction moments (pKAM) also differed across tasks. Peak vertical ground reaction force (pVGRF) was highest in SLDVJ whereas the medial knee displacement (MD) was highest in the BDVJ.

Table 5.2 Descriptive data of variables across tasks (female, n=41 and male, n=46) participants

| Task | Variable | KAA deg | pKAM $Nm.kg^{-1}$ | pKFA deg | pVGRF BW | MD cm |
|---|---|---|---|---|---|---|
| BDVJ | F DOM | 0.7 ± 3.6 | 0.41 ± 0.18 | -98.0 ± 10.9 | 1.66 ± 0.32 | 2.6 ± 1.7 |
| | F NDOM | 0.7 ± 3.1 | 0.29 ± 0.11 | -97.2 ± 10.7 | 1.55 ± 0.38 | 3.3 ± 2.3 |
| | M DOM | 2.3 ± 3.7 | 0.34 ± 0.20 | -97.3 ± 13.2 | 1.76 ± 0.43 | 4.9 ± 2.9 |
| | M NDOM | 2.7 ± 4.5 | 0.27 ± 0.17 | -96.7 ± 13.6 | 1.56 ± 0.32 | 5.7 ± 3.2 |
| SLDVJ | F DOM | -0.3 ± 3.3 | 0.43 ± 0.23 | -67.2 ± 8.8 | 3.47 ± 0.43 | 2.1 ± 1.3 |
| | F NDOM | -0.5 ± 2.7 | 0.25 ± 0.16 | -66.1 ± 7.8 | 3.46 ± 0.42 | 1.5 ± 1.2 |
| | M DOM | 1.5 ± 3.2 | 0.35 ± 0.18 | -68.9 ± 9.4 | 3.40 ± 0.53 | 3.0 ± 1.3 |
| | M NDOM | 1.2 ± 3.2 | 0.26 ± 0.15 | -67.0 ± 8.8 | 3.46 ± 0.49 | 3.1 ± 1.4 |
| SLHOP | F DOM | -2.3 ± 3.3 | 0.30 ± 0.13 | -61.8 ± 9.2 | 2.86 ± 0.40 | 1.2 ± 1.1 |
| | F NDOM | -2.1 ± 2.7 | 0.12 ± 0.12 | -60.6 ± 8.6 | 2.83 ± 0.42 | 0.9 ± 1.0 |
| | M DOM | -0.4 ± 3.0 | 0.22 ± 0.16 | -58.8 ± 7.9 | 3.05 ± 0.59 | 1.5 ± 1.3 |
| | M NDOM | -0.8 ± 3.1 | 0.13 ± 0.16 | -56.7 ± 8.2 | 3.05 ± 0.49 | 1.7 ± 1.1 |
| SS | F DOM | -2.6 ± 4.0 | 0.52 ± 0.89 | -52.9 ± 6.1 | 3.02 ± 0.42 | - |
| | F NDOM | -1.8 ± 2.8 | 0.34 ± 0.41 | -52.8 ± 7.2 | 2.95 ± 0.47 | - |
| | M DOM | 0.2 ± 3.7 | 0.38 ± 0.72 | -52.4 ± 5.2 | 3.04 ± 0.39 | - |
| | M NDOM | -0.4 ± 3.7 | 0.47 ± 0.59 | -52.0 ± 4.7 | 3.03 ± 0.39 | - |

*BDVJ bilateral, drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; KAA, knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; F, female; M, male; D, dominant leg; NDOM, non-dominant leg.*
*Values are reported as mean ± standard deviation. IC, initial contact; VGRF, vertical ground reaction force; deg, degrees; BW, body weight.*

### 5.3.1 Coefficient of variation

For males, the KAA at initial contact for SS in the dominant (DOM) leg revealed the highest coefficient of variation of 17.02% (Table 5.3). For females, SLDVJ has the highest coefficient of variation for the KAA at initial contact.

Table 5.3 Coefficient of variation (%) across tasks

| Female | KAA | pKAM | pKFA | pVGRF | MD |
|---|---|---|---|---|---|
| BDVJ DOM | 5.02 | 0.45 | 0.11 | 0.20 | 0.68 |
| BDVJ NDOM | 4.35 | 0.37 | 0.11 | 0.25 | 0.69 |
| SLHOP DOM | 1.45 | 0.43 | 0.15 | 0.14 | 0.87 |
| SLHOP NDOM | 1.29 | 1.00 | 0.14 | 0.15 | 1.01 |
| SS DOM | 1.53 | 1.73 | 0.11 | 0.14 | - |
| SS NDOM | 1.56 | 1.22 | 0.14 | 0.16 | - |
| SLDVJ DOM | 11.38 | 0.53 | 0.13 | 0.12 | 0.66 |
| SLDVJ NDOM | 5.96 | 0.65 | 0.12 | 0.12 | 0.79 |
| Male | KAA | pKAM | pKFA | pVGRF | MD |
| BDVJ DOM | 1.61 | 0.57 | 0.14 | 0.24 | 0.60 |
| BDVJ NDOM | 1.65 | 0.65 | 0.14 | 0.20 | 0.56 |
| SLHOP DOM | 7.56 | 0.72 | 0.13 | 0.19 | 0.84 |
| SLHOP NDOM | 3.82 | 1.28 | 0.14 | 0.16 | 0.66 |
| SS DOM | 17.02 | 1.91 | 0.10 | 0.13 | - |
| SS NDOM | 9.87 | 1.25 | 0.09 | 0.13 | - |
| SLDVJ DOM | 2.17 | 0.53 | 0.14 | 0.15 | 0.45 |
| SLDVJ NDOM | 2.75 | 0.59 | 0.13 | 0.14 | 0.45 |

*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; DOM, dominant leg; NDOM, non-dominant leg.*

### 5.3.2 Relationships between tasks

Generally, significant relationships were seen across all tasks. For KAA, 23 out of 24 were significant for both female and male dominance except for the BDVJ and SS pair in female non-dominant (NDOM). Yet, 18 out of 24 of the pVGRF were seen to be not significant except for both female and male SLDVJ and SLHOP, and male's BDVJ and SLDVJ. Very few variables showed a good to strong correlation (Table 5.4). A moderate to good correlation was observed for the KAA at initial contact ($\rho$ = 0.43 – 0.86) in both males and females. KAA at initial contact for the pair SLDVJ and SLHOP in both male and female for DOM and NDOM leg showed a good correlation ($\rho$ = 0.81 - 0.86). Poor correlations were seen in the female NDOM limb for the BDVJ and SLHOP and, BDVJ and SS. The pKAM displayed a very poor to moderate correlation ($\rho$ = 0.06 – 0.67) across tasks. The lowest was seen for the SLDVJ and SS in female NDOM and both male DOM and NDOM. pKFA for both female and male in both DOM and NDOM limb revealed a very poor to moderate correlation across tasks ($\rho$ = -0.07 – 0.96). Only male NDOM for the BDVJ and SLDVJ pair has shown good spearman $\rho$ of 0.71. Nearly all of the pVGRF and MD showed poor to very poor correlation across tasks ($\rho$ = 0.33 - -0.02). A consistent moderate to good correlation was seen between the SLDVJ and SLHOP across all risk factors with spearman $\rho$ of 0.41 to 0.86 for both female and male and all were seen to be significant.

Table 5.4 Spearman's rank correlation coefficients for the risk factors across different tasks

| Spearman's rho | | KAA | | pKAM | | pKFA | | pVGRF | | MD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **F DOM** | **F NDOM** | **F DOM** | **F NDOM** | **FDOM** | **FNDOM** | **F DOM** | **F NDOM** | **F DOM** | **F NDOM** |
| BDVJ - SLDVJ | Correlation Coefficient | 0.64** | 0.47** | 0.67** | 0.49** | 0.62** | 0.54** | 0.26 | 0.24 | 0.30 | 0.07 |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.13 | 0.06 | 0.68 |
| BDVJ - SLHOP | Correlation Coefficient | 0.55** | 0.39* | 0.63** | 0.40* | 0.23 | 0.07 | 0.29 | 0.01 | 0.30 | 0.08 |
| | *P* value | 0.00 | 0.01 | 0.00 | 0.01 | 0.15 | 0.67 | 0.07 | 0.96 | 0.06 | 0.62 |
| BDVJ - SS | Correlation Coefficient | 0.58** | 0.28 | 0.39* | 0.21 | 0.42** | 0.38* | 0.21 | 0.20 | | |
| | *P* value | 0.00 | 0.08 | 0.01 | 0.19 | 0.01 | 0.02 | 0.19 | 0.21 | | |
| SLDVJ - SLHOP | Correlation Coefficient | 0.85** | 0.85** | 0.65** | 0.58** | 0.46** | 0.36* | 0.41** | 0.49** | 0.58** | 0.58** |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| SLDVJ - SS | Correlation Coefficient | 0.72** | 0.64** | 0.58** | 0.15 | 0.60** | 0.55** | 0.10 | 0.09 | | |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.35 | 0.00 | 0.00 | 0.54 | 0.57 | | |
| SLHOP - SS | Correlation Coefficient | 0.66** | 0.60** | 0.48** | 0.50** | 0.35* | 0.38* | 0.25 | 0.04 | | |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.02 | 0.12 | 0.82 | | |

* Colour chart

| r value | 0.00 to 0.19 | 0.20 to 0.39 | 0.40 to 0.69 | 0.70 to 0.89 | 0.90 to 1.00 |
|---|---|---|---|---|---|

***Correlation is significant at the 0.01 level (2-tailed).*
**Correlation is significant at the 0.05 level (2-tailed).*
*[a]KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; F, female; DOM, dominant leg; NDOM, non-dominant leg.*

| Spearman's rho | | KAA | | pKAM | | pKFA | | pVGRF | | MD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | M DOM | M NDOM | M DOM | M NDOM | M DOM | M NDOM | M DOM | M NDOM | M DOM | M NDOM |
| BDVJ - SLDVJ | Correlation Coefficient | 0.50** | 0.64** | 0.41** | 0.46** | 0.67** | 0.71** | 0.43** | 0.33* | 0.17 | 0.42** |
| | *P* value | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.25 | 0.00 |
| BDVJ - SLHOP | Correlation Coefficient | 0.43** | 0.51** | 0.57** | 0.51** | 0.46** | 0.37* | 0.27 | -0.02 | 0.06 | 0.55** |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.07 | 0.87 | 0.68 | 0.00 |
| BDVJ - SS | Correlation Coefficient | 0.44** | 0.56** | 0.28 | 0.36* | -0.07 | 0.29 | -0.02 | -0.02 | | |
| | *P* value | 0.00 | 0.00 | 0.06 | 0.01 | 0.65 | 0.05 | 0.88 | 0.89 | | |
| SLDVJ - SLHOP | Correlation Coefficient | 0.86** | 0.81** | 0.52** | 0.55** | 0.69** | 0.62** | 0.52** | 0.50** | 0.68** | 0.67** |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SLDVJ - SS | Correlation Coefficient | 0.69** | 0.61** | 0.06 | 0.20 | 0.19 | 0.50** | -0.02 | 0.05 | | |
| | *P* value | 0.00 | 0.00 | 0.68 | 0.19 | 0.21 | 0.00 | 0.90 | 0.75 | | |
| SLHOP - SS | Correlation Coefficient | 0.68** | 0.73** | 0.43** | 0.27 | 0.26 | 0.29* | -0.02 | 0.14 | | |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.07 | 0.08 | 0.05 | 0.92 | 0.37 | | |

* Colour chart

| r value | 0.00 to 0.19 | 0.20 to 0.39 | 0.40 to 0.69 | 0.70 to 0.89 | 0.90 to 1.00 |
|---|---|---|---|---|---|

***Correlation is significant at the 0.01 level (2-tailed).*

**Correlation is significant at the 0.05 level (2-tailed).*

[a]*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; M, male; DOM, dominant leg; NDOM, non-dominant leg.*

### 5.3.3 Leg Dominance

Significant differences between limbs ($P < 0.05$) were found in the pKAM (Table 5.5) for both females and males across tasks except for SS. A significant difference was also found for the female MD for the SLDVJ DOM and SLDVJ NDOM. pVGRF in BDVJ for males were also significantly different between limbs. The rest of the data showed no significant differences for leg dominance.

Table 5.5 A comparison of the differences between dominant and non-dominant legs

| Female | KAA | pKAM | pKFA | MD | pVGRF |
|---|---|---|---|---|---|
| BDVJ DOM vs BDVJ NDOM | 0.987 | 0.001* | 0.204 | 0.184 | 0.190 |
| SLDVJ DOM vs SLDVJ NDOM | 0.735 | 0.000* | 0.168 | 0.018* | 0.855 |
| SLHOP DOM vs SLHOP NDOM | 0.668 | 0.000* | 0.129 | 0.142 | 0.504 |
| SS DOM vs SS NDOM | 0.117 | 0.204 | 0.853 | - | 0.216 |

| Male | KAA | pKAM | pKFA | MD | pVGRF |
|---|---|---|---|---|---|
| BDVJ DOM vs BDVJ NDOM | 0.533 | 0.022* | 0.203 | 0.252 | 0.009* |
| SLDVJ DOM vs SLDVJ NDOM | 0.464 | 0.020* | 0.560 | 0.736 | 0.204 |
| SLHOP DOM vs SLHOP NDOM | 0.261 | 0.001* | 0.368 | 0.256 | 0.949 |
| SS DOM vs SS NDOM | 0.347 | 0.413 | 0.678 | - | 0.863 |

**Paired t-test significant at the 0.05 level (2-tailed)*
*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; DOM, dominant leg; NDOM, non-dominant leg.*

### 5.3.4 Quintiles: Rank score and Absolute sum of error

Figure 5.4 is the quintile colour-map illustrating summed rank score by quintile (a,b,e,f) and absolute sum of error (c,d,g,h). Generally, both sexes DOM and NDOM legs have distinct patterns across variables. KAA rank scores identify the highest number of participants who remain in the same quintile rank for both sex and dominance, particularly for female DOM (a) where 5 out of 8 participant from $5^{th}$ quintile remained in the same rank across tasks (Table 5.6). While pVGRF rank score did not identified any participant who remained in the same quintile. Overall, females had the highest total number of participants remaining in the same rank compared to males.

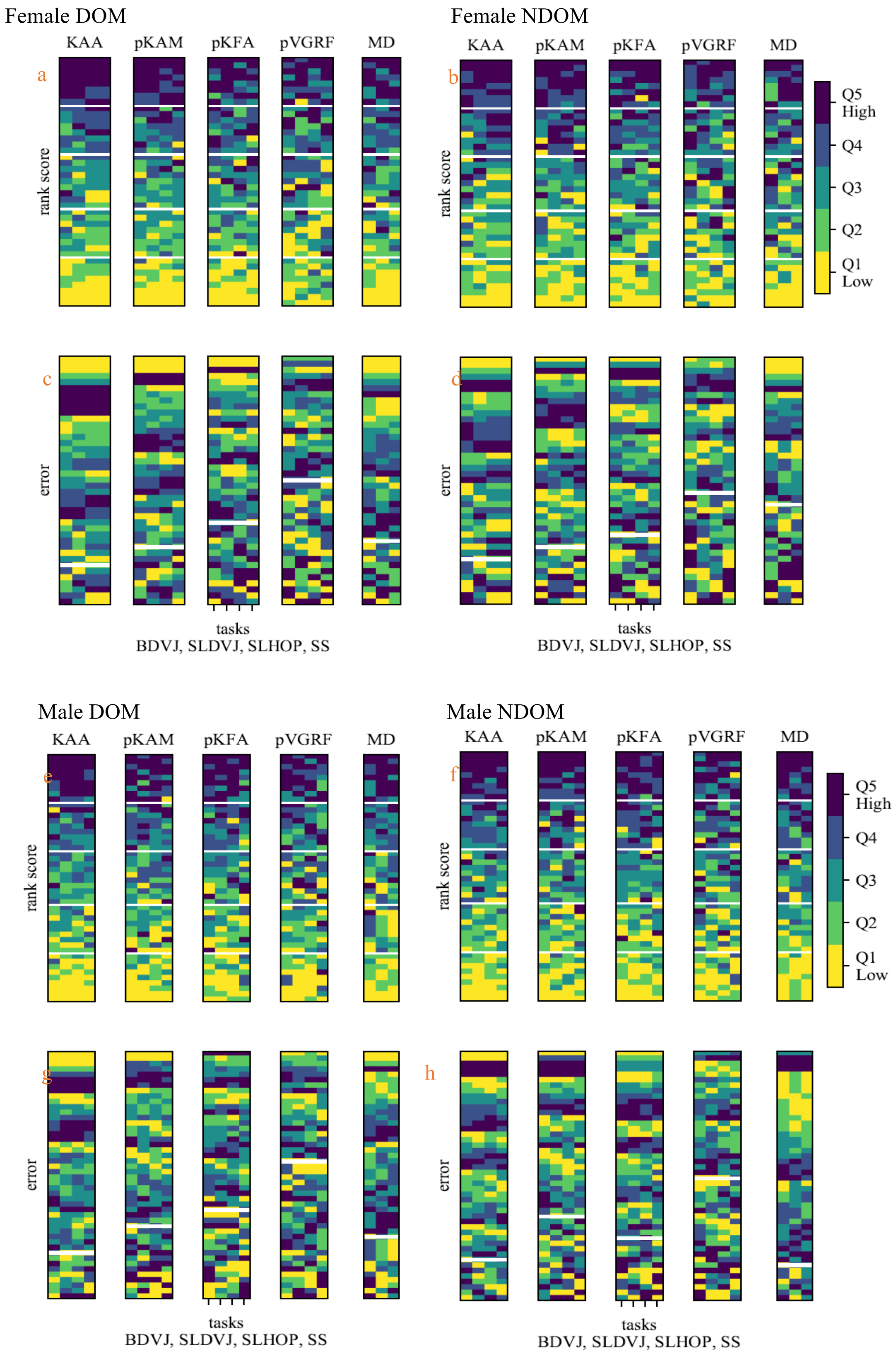



Figure 5.4 Quintile colour-map illustrating summed rank score by quintile and absolute sum of error. The median-error of the absolute sum of error score was annotated onto each of the absolute sum of error column (white line).

Table 5.6 Number of participant who remained in the same quintile rank across tasks

| n = 41 | F DOM | | | | | F NDOM | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Tasks / Quintile | KAA | pKAM | pKFA | pVGRF | MD | KAA | pKAM | pKFA | pVGRF | MD |
| Q5 (n=8) | 5 | 2 | 1 | 0 | 1 | 2 | 1 | 2 | 0 | 1 |
| Q4 (n=8) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Q3 (n=9) | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| Q2 (n=8) | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| Q1 (n=8) | 3 | 3 | 2 | 0 | 3 | 2 | 1 | 1 | 0 | 3 |

| n = 46 | M DOM | | | | | M NDOM | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Tasks / Quintile | KAA | pKAM | pKFA | pVGRF | MD | KAA | pKAM | pKFA | pVGRF | MD |
| Q5 (n=9) | 3 | 0 | 1 | 0 | 1 | 3 | 3 | 0 | 0 | 3 |
| Q4 (n=9) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Q3 (n=10) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Q2 (n=9) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Q1 (n=9) | 3 | 2 | 0 | 0 | 2 | 2 | 1 | 1 | 0 | 0 |

*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; DOM, dominant leg; NDOM, non-dominant leg.*

The absolute sum of error for the pVGRF displayed the highest median-error line (Figure 5.3 – c,d,g,h) and the smallest amount of participants ranked above the median-error line ranged between 20 to 23 participants for both sex and dominance (Table 5.7). The highest number of participants above the median-error line ranged between 34 to 38 for KAA and between 24 to 39 for MD. A low location of the median-error lines indicates that there are more participants who remain within the same quintile rank across tasks than those who do not. The number of participants that remained within the same quintile rank for the particular risk factor contributes to the strength of the correlational relationship.

Table 5.7 Number of participants above the absolute sum of error median-error line

| | F DOM | F NDOM n = 41 | M DOM | M NDOM n = 46 |
|---|---|---|---|---|
| KAA | 34 | 33 | 37 | 38 |
| pKAM | 30 | 30 | 32 | 30 |
| pKFA | 27 | 29 | 29 | 34 |
| pVGRF | 20 | 22 | 20 | 23 |
| MD | 30 | 24 | 34 | 39 |

*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; DOM, dominant leg; NDOM, non-dominant leg.*

### 5.3.5 Movement Signatures

High numbers of task-invariant movement signatures was observed; out of the total number of legs and risk factors per participants (n=870), 245 individual movement signatures were seen (Table 5.8). When sorted across participants, both female DOM and NDOM displayed quite similar patterns for KAA and pKAM (Figure 5.5). Whereas only KAA displayed a similar pattern across tasks for male DOM and NDOM. Of all the variables, the highest amount of movement signature was identified for different variables across participant groups; MD in female DOM, KAA in female NDOM, KAA and MD in male DOM, and MD in male DOM. pVGRF movement signature was seen to be the lowest for both sex and dominance. pKAM movement signature was identified more in females than males.

Table 5.8 Total identified movement signature for each risk factor

| | F DOM | F NDOM | M DOM | M NDOM |
|---|---|---|---|---|
| | n = 41 | | n = 46 | |
| KAA | 19 | 16 | 17 | 15 |
| pKAM | 16 | 12 | 7 | 11 |
| pKFA | 9 | 8 | 7 | 13 |
| pVGRF | 6 | 6 | 6 | 2 |
| *MD | 20 | 14 | 17 | 24 |
| Total | 70 | 56 | 54 | 65 |

*KAA, Knee abduction angle at initial contact; pKAM, peak knee abduction moment; pKFA, peak knee flexion angle; pVGRF, peak vertical ground reaction force; MD, medial knee displacement; DOM, dominant leg; NDOM, non-dominant leg.*
** MD movement signatures was easier to be identified as it was only observe for BDVJ, SLDVJ and SLHOP.*

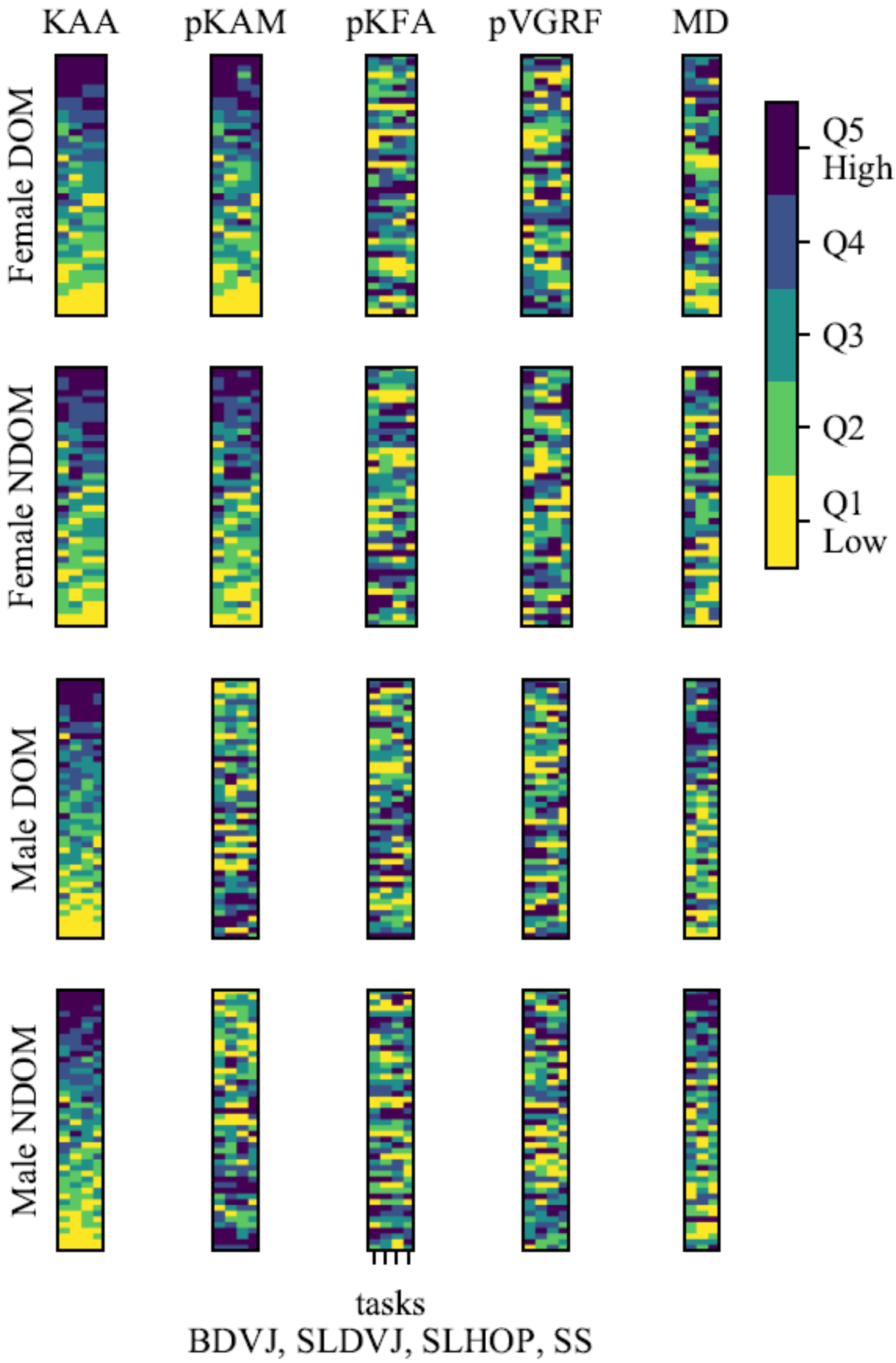



Figure 5.5 From left to right, each colour-map was sorted across participants i.e. row 1 is the same participant across all variables, to illustrate how participants ranked across all risk factors and tasks.

35 out of 41 female DOM, 29 out of 41 in female NDOM, 37 out of 46 male DOM and 39 out of 46 male NDOM were identified with movement signature. Of all participants and legs (n=174), 140 legs were identified with at least one type (risk factor) of movement signature. Unique movement signatures were identified across all participants, illustrating combinations of movement signatures with different variables (risk factors) that a participant has (Table 5.9). A MD only movement signature was identified the most amongst the participants however; with the notion that MD was only calculated for BDVJ, SLDVJ and SLHOP.

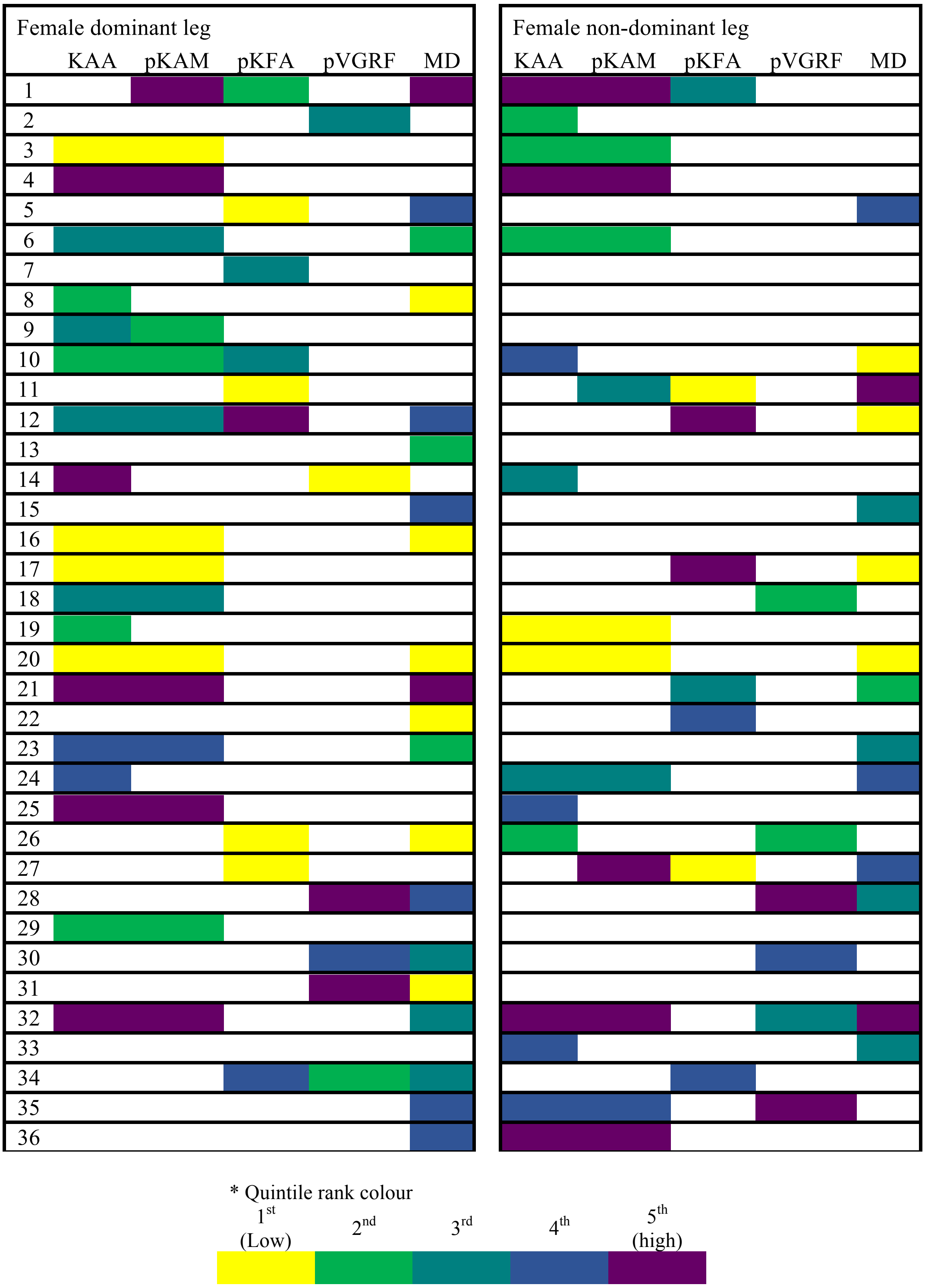
Table 5.9 Total number of participants' unique movement signatures identified across participants. Unique movement signatures are the compilation of movement signatures identified for each individuals.

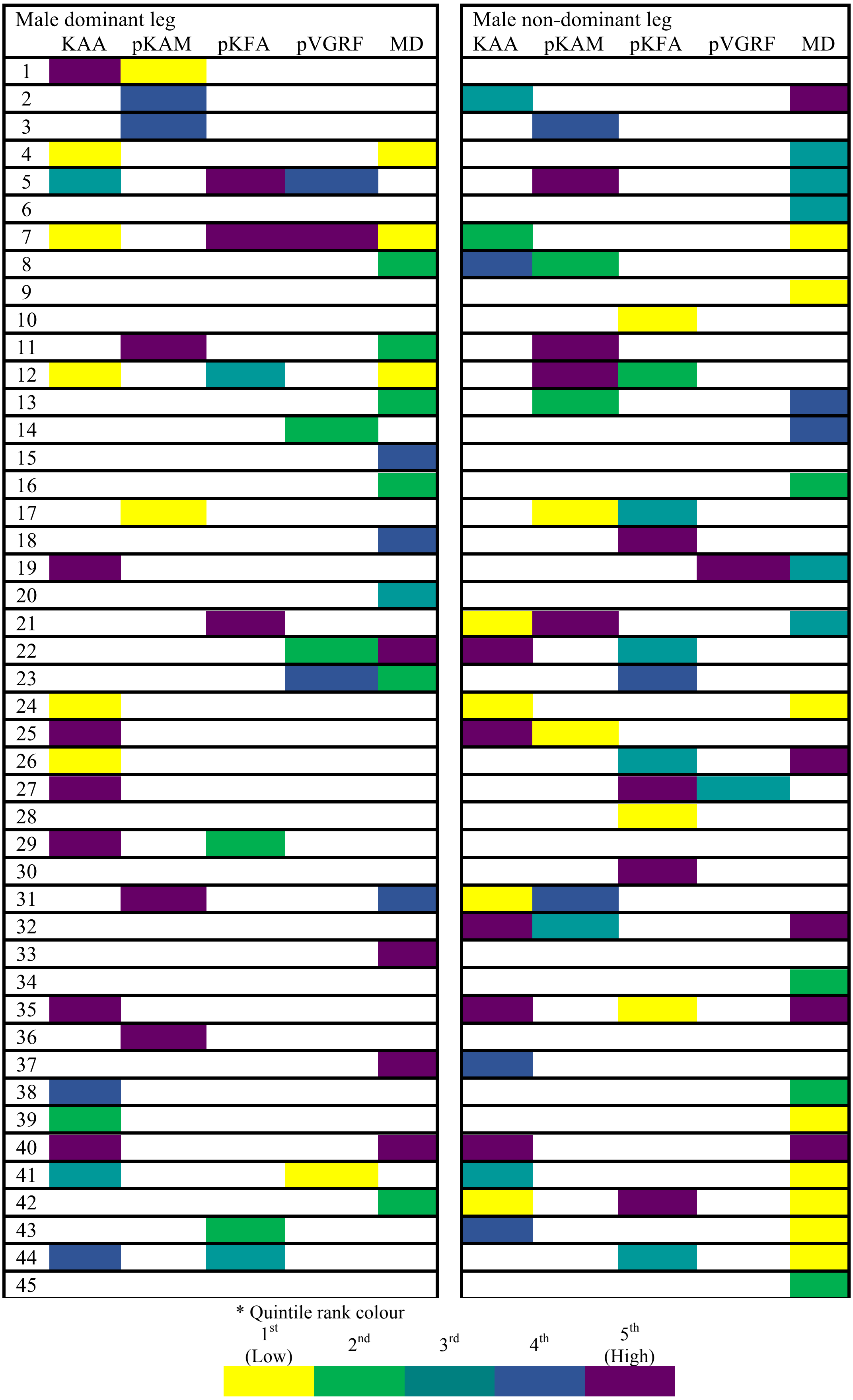
| Unique Movement Signatures | F DOM n=41 | F NDOM n=41 | M DOM n=46 | M NDOM n=46 |
|---|---|---|---|---|
| KAA | 2 | 3 | 8 | 1 |
| KAA, MD | 1 | 2 | 2 | 6 |
| KAA, pKAM | 7 | 5 | 1 | 3 |
| KAA, pKAM, MD | 6 | 2 | | 2 |
| KAA, pKAM, pKFA | 1 | 1 | | |
| KAA, pKAM, pKFA, MD | 1 | | | |
| KAA, pKAM, pVGRF | | 1 | | |
| KAA, pKAM, pVGRF, MD | | 1 | | |
| KAA, pKFA | | | 2 | 1 |
| KAA, pKFA, MD | | | 1 | 2 |
| KAA, pKFA, pVGRF | | | 1 | |
| KAA, pKFA, pVGRF, MD | | | 1 | |
| KAA, pVGRF | 1 | 1 | 1 | |
| MD | 5 | 3 | 9 | 9 |
| pKAM | | | 4 | 2 |
| pKAM, MD | | | 2 | 2 |
| pKAM, pKFA | | | | 2 |
| pKAM, pKFA, MD | 1 | 2 | | |
| pKFA | 3 | 2 | 2 | 5 |
| pKFA, MD | 2 | 3 | | 2 |
| pKFA, pVGRF | | | | 1 |
| pKFA, pVGRF, MD | 1 | | | |
| pVGRF | 1 | 2 | 1 | |
| pVGRF, MD | 3 | 1 | 2 | 1 |
| Total number of unique movement signatures = 24 | 35 | 29 | 37 | 39 |

### 5.4.6 Highly ranked movement signatures

Overall, 17 out of 35 female DOM, 18 out of 29 female NDOM, 23 out of 37 male DOM and 24 out of 39 male NDOM with unique movement signatures were identified as being highly ranked ($4^{th}$ and $5^{th}$ quintile) (Table 5.10). Out of the 140 unique movement signatures observed, 82 were highly ranked. Five high-ranked KAA movement signatures identified in female DOM an NDOM were in combination with highly ranked pKAM movement signature. In males there were no KAA and pKAM combination movement signatures. High ranked movement signatures did not necessarily come from the same participants.

Table 5.10 The table below illustrates each participant's unique movement signatures and its quintile rank. Different colour blocks represent different movement signature rankings.




Male dominant leg
KAA pKAM pKFA pVGRF MD
Male non-dominant leg
KAA pKAM pKFA pVGRF MD
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
* Quintile rank colour
1st (Low)
2nd
3rd
4th
5th (High)

## 5.4 Discussions

This study had two main aims, firstly to identify if risk factors ranked individuals consistently across five different dynamic tasks. Our results showed that KAA at initial contact provided moderate to good correlations across tasks but other risk factors had generally poor correlations. KAA therefore appears to be the best candidate variable to represent task-invariant behaviours. The SLDVJ and SLHOP pair were ranked most consistently across all risk factors, which could indicate that risk factors translate better across tasks with a similar movement technique/pattern. A second aim was to identify if task-invariant movement signatures were present. Several movement signatures were identified for the existing prospective risk factors. The analysis indicated that the highest number of movement signatures was different across participants, though a pVGRF movement signature occurred least frequently across all participants and dominance. Moreover, pKAM movement signatures were identified more in females than males. Interestingly, the combination of high ranked (undesirable) KAA and pKAM movement signatures was only observed in females. Undesirable movement signatures appeared independently between legs.

### 5.4.1 Correlation Results: Cohort analysis

Substantial differences were observed between bilateral and single-legged tasks means (Table 5.2). In particular, the pVGRF had the lowest correlation between the single-legged and bilateral leg task. Whilst it is expected that a single-legged task would produce a greater vertical ground reaction force than a bilateral task (Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Yeow, Lee, & Goh, 2010) the relationship between these was inconsistent between subjects. This likely indicates that a different dynamic strategy governs the amount of whole-body loading in single leg versus bilateral tasks within individuals. In addition, increased forces can also be seen when an elevated starting point was added to the task, whilst increasing the demands of the overall task (Harty et al., 2011). Distinct kinematic differences can also be seen in the current study for pKFA between bilateral and single-legged tasks. This is likely due to the nature of the bilateral task, as individuals have more flexibility, stability and combined strength to hold themselves in a flexed position (Moore, Mulloy, Bridle, & Mullineaux, 2016).

By comparing multiple risk factors across multiple bilateral and unilateral tasks in a reasonably large sample, this study offers unique insights adding to the findings from previous studies. With reference to the tasks evaluated, our results showed mostly moderate correlation for the frontal plane risk factors. This is similar to Harty et al. (2011) who observed across single-legged and bilateral tasks, however, our results were also supported by Kristianslund and Krosshaug (2013)'s findings where a poor to moderate correlation was seen between a bilateral task and a sudden change of direction task.

Previous studies comparing risk factors across tasks have also found strong to moderate relationships between single-legged and bilateral tasks in knee angles and moments (Harty et al., 2011). This was also shown in our results comparing BDVJ and SLDVJ tasks, where a moderate correlation was observed. They have suggested that even though single-legged and bilateral tasks were very different in terms of physical demands, when observing peak knee abduction angle and pKAM; similar dynamic control of lower extremity and knee position across step-down, single leg landing and BDVJ could be seen (Harty, 2011). The pKAM in our study was seen to be mostly moderately correlated across bilateral and single-legged tasks except for BDVJ and SS pair which was aligned with Kristianslund and Krosshaug (2013)'s investigation. Kristianslund and Krosshaug (2013) also found that the pKAM was six times higher in SS. Moreover, a high knee abduction moment in SS would not necessarily predict a high knee abduction moment in BDVJ as motion patterns between these two tasks are different especially when a SS task is known for its highly-dynamic movement with rapid change of direction while the BDVJ is a controlled bilateral-legged task (Kristianslund & Krosshaug, 2013). Another possible reason for these differences could also be that the bilateral tasks could not effectively represent the lower body movements and injury risk that occurs during a single-legged task (Taylor et al., 2016). However, when comparing this across single-legged tasks only, moderate to good correlations have been seen for peak knee abduction angle and pKAM (Jones et al., 2014). Multiple studies have suggested that a correlational relationship between tasks means that individuals at risk are likely to show this characteristic across tasks (Harty et al., 2011; Jones et al., 2014). This had not been confirmed with an analysis of individual responses.

Someone who is at risk of performing undesirable behaviour during the execution of a task can usually be visually identified as showing consistently poor kinematics while performing a task e.g. using dynamic valgus to screen for ACL injury risk (Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009; McLean et al., 2005; Munro, Herrington, & Comfort, 2017; Padua et al., 2009). In this study only KAA correlated well across tasks indicating most of the risk factors observed did not transfer across tasks (Table 5.4), and this has also been observed in a study by Heebner et al (2017). The inconsistency in ranking between tasks might suggest that there is no generic motor pattern across the tasks. This does not necessarily mean however that there is no common underlying muscle synergy across a variety of tasks as the global demands of these tasks are the same. There may well be general synergies, but that are then refined according to the specific task, leading to different biomechanics. An understanding beyond biomechanics such as the influence of the motor control, movement patterns and learning processes, prior to and during task execution, warrants further research.

Frontal plane motion is one of the key components of proposed ACL injury mechanisms and excessive movements in the frontal plane outside the normal range are undesirable (Chaudhari & Andriacchi, 2006; Hewett et al., 2005; T. W. Kernozek, Torry, H, Cowley, & Tanner, 2005; Koga et al., 2010; Shimokochi & Shultz, 2008; Taylor, Ford, Nguyen, & Shultz, 2016). There was moderate correlation for pKAM; however, the correlation was moderate-to-good for the KAA. The KAA therefore, appears to be the best candidate variable to represent an individual's behaviour across tasks. Though, an opposite interpretation could be that, namely KAA in reality captures the behaviour prior to contact with the ground, and one could expect that dangerous task-specific loading patterns that take place during the first part of the contact phase (often referred to as weight acceptance phase) are not captured. Moreover, at initial contact this variable does not inform us of how the posture changes in response to load or after contact. Although KAA shows a consistent ranking across tasks, the consistency of an individual's response to the landing phase was not captured. Therefore, further investigation of the knee abduction angle regarding the changes and response to loading warrants further exploration.

There are two ways in which variability of the prospective variables would affect participant ranking. Peak values may have a greater scope to change between tasks as an individual has from initial contact to take off, to produce their peak loads or values. The KAA at initial contact were distributed consistently across tasks with $\rho$ of 0.85 and a coefficient of variation of 11.38 and 1.45 for SLDVJ and SLHOP respectively (Appendix J). Meanwhile, the moderate correlation illustrated by the SLDVJ and SS pair ($\rho$ of 0.50) has shown that one of the tasks had likely insufficient variation in the pKFA which in this case was the SS (coefficient of variation of 0.09). When both tasks' coefficient of variation values are large, it indicates the data is reasonably spread relative to the mean and leads to better correlations. Consequently, this is a limitation in using rank correlations. As no between day data collection was collected, the reliability of some variables between days are unknown and the effect it has on identifying an individual's movement signature are therefore uncertain. Studies by Malfait et al. (2014) and Sankey et al. (2015) both using the same model as described in this thesis conducted reliability studies into the drop vertical jump and sidestep respectively and considered some of the variables being examined here. Specifically they compared inter-trial, intra observer (between session) and inter-observer reliability. For this study (and with respect to the reliability of movement signatures described later) the most relevant data would be from the between-session reliability; for the BDVJ knee and hip kinematic and kinetic variables ranged from 1.9 – 5.7° and 5.9 - 19.8 Nm (Malfait et al., 2014) and for SS knee kinematics between 2 - 5° and 20-42 Nm for knee moments in the weight acceptance phase (Sankey et al., 2015). Though as only one variable in one task was seen to indicate high variability between days, this could perhaps influence the reliability of the particular task however, as this was not particularly the main objective of this study, the movement signatures observed were considered as reliable.

### 5.4.2 Movement Signatures: Individual Analysis

When characteristics of an individual can be identified across different tasks, this demonstrates the existence of the individual's movement signature. As these task-invariant behaviours are likely to be hard-wired, it also represents the individual's behaviour. To begin to determine a movement signature the individual rankings were summed.

Our observation showed a high number of movement signatures (245 out of the total number of legs and risk factors per participants, n=870 legs) which suggests that certain individuals have task-invariant movement signatures. Our study further showed that individuals have task-invariant movement patterns not only in single-legged tasks, but across bilateral and highly dynamic tasks as well (Harty et al., 2011; Jones et al., 2014). Our findings further support the use of dynamic tasks to screen for ACL injuries as movement signatures were seen across all of our tasks, however, this is limited to the four tasks that we tested in our study. Further investigations involving other tasks that involve a more 'real-world scenario' such as adding a defender or receiving a ball in a sidestepping task (Kristianslund & Krosshaug, 2013; Mok, Bahr, & Krosshaug, 2017) are warranted to further understand actual sport-like behaviours.

Overall, 140 unique movement signatures were noted out of the total number of legs and risk factors per participant (n=870) (Table 5.9). This observation indicates that individuals have their own unique task-invariant movement traits/patterns across tasks which could provide vital information when designing an individual's injury prevention program. Information from these unique movement signatures could be use to inform specific movement patterns or behaviours of the athletes which could be beneficial for coaches or sport scientist to tailor programs specific to the athlete's need. For an example, for athletes who were identified with a pKFA only movement signature could indicate that the particular athlete may have an underlying neuromuscular deficits in their posterior chain and programs that could reduce knee valgus and increase knee flexion such as plyometric and jump trainings can help coaches to specifically tailor programs to cater to the strengthening of the athlete's hamstrings and other targeted muscle areas. Having this information could perhaps increase the effectiveness of the individualised program.

### 5.4.3 Undesirable (high ranked) movement signatures

Out of the 140 unique movement signatures (Table 5.9), 82 highly ranked movement signatures (Table 5.10) are likely most important from an injury perspective as the highly ranked movement signatures are the ones indicative of "at-risk" movement. Based on these findings, the present study showed that task-invariant movement signatures may well identify potential high-risk individuals as more than half of the participants with movement signatures were highly ranked.

The KAA and MD movement signature was seen the most highly ranked across participants. However, MD movement signatures were not observed for SS, therefore its value is possibly overestimated when compared to the rest of the risk factors. However, our main aim was to observe the rank consistency across all single-legged and bilateral tasks in order to identify task-invariant behaviours that cover almost the whole dynamic (sport-specific) aspect of the injury incidence. As for KAA movement signatures, our study observed this risk factor at initial contact, where previous studies observed peak knee abduction angle at landing; nonetheless, these studies have observed frontal plane risk factors to be consistent within their evaluated tasks (Harty et al., 2011; Jones et al., 2014). The least occurring high ranked movement signature across participants identified was pVGRF. Though this was unsurprising as pVGRF was seen very poorly correlated between tasks in this present study and another (Harty et al., 2011). The least occurring pVGRF movement signature could possibly be due to the demands of the task-dependent foot landing techniques that influences the overall biomechanical loads (Cortes, Morrison, Van Lunen, & Onate, 2012).

An interesting finding was seen when comparing females and males as highly ranked KAA and pKAM combination movement signatures were only present in our female participants. Male participants did not show the combination of a KAA and pKAM movement signature. This finding could be linked to the multi-planar injury mechanism seen in females and a more single plane mechanism in males (Quatman & Hewett, 2009). Therefore our findings could perhaps also be aligned with the findings of Hewett (2005)'s prospective study, that identified KAA and pKAM as predictors of ACL injury in females. However, as no prospective study on the biomechanical risk factors of ACL injury was done yet in males, we could not conclude which risk factors are the best to screen for injury. Even though there is no prospective evidence for ACL injury risk factors in males, the highly ranked movement signatures may serve as a guide to what risk factor that is most valuable in identifying at-risk males.

Not all of the movement signatures were highly ranked and movement signatures identified in DOM leg were not necessarily seen in NDOM leg of the same participant, i.e. only two female participants had highly ranked KAA and pKAM movement signatures in both legs and three male participants had highly ranked KAA movement signatures in both legs. This could possibly be justified by the different outcomes found in previous studies where one study indicated that females tend to injure their ACL on the NDOM leg and males were seen to injure their ACL on the DOM leg (Brophy et al., 2010). Meanwhile, our findings for leg dominance were consistent with previous investigations which found lack of differences based on leg dominance (Greska, Cortes, Ringleb, Onate, & Van Lunen, 2017; Negrete, Schick, & Cooper, 2007).

### 5.4.3 Moving towards a different perspective

This new approach of identifying injury risk informs us of the existence of task-invariant movement signatures. The presence of a highly ranked movement signature representative of task-invariant behaviour could be linked to increased risk of incurring an ACL injury. Observing existing patterns or behaviour (regularities) of the risk factor interactions across tasks could lead to an advancement of risk-profile identification (Bittencourt et al., 2016). Relying on the probability of the occurrence of recognisable regularities, i.e. a movement signature, could maximize one's chances to better predicting injury occurrence (Bittencourt et al., 2016). As presented in Table 5.5, there were inconsistent correlations across risk factors and tasks, which could represent the complexity of injury prediction. Bittencourt et al. (2016) describe sports injuries as ever-changing complex incidents that encompass many possible interactions and determinants, which in the end lead to the injury. In their review, they have illustrated how the complexity of an ACL injury differs between a basketball player and a ballet dancer. Even though both of these individuals have the same injury, the magnitude or determinants of the risk factors interaction and configuration among factors are different. KAA at initial contact perceived as the best candidate to best predict ACL injury however, it only informs us of the frontal plane posture of the knee at that particular instance in time. Further detailed examination shows that task-invariant movement signatures could potentially provide better identification of an individual's injury risk. Nonetheless, when utilising this new approach, careful consideration should be taken for the risk factor, participant and dominance selection as it may influence the outcome of the movement signature.

In this study, the approach to identifying movement signatures was based on established biomechanical risk factors. As there are only a very limited number of prospective studies in females and none in males, and considering that none of the previously identified risk factors was a strong predictor of ACL injuries, an alternative approach through the identification of movement signatures can be justified. It is well documented that combinations of loads are important for an ACL strain and during dynamic sporting activities, the typical ACL injury mechanism is multi-planar (Kiapour et al., 2014; Quatman et al., 2010). The knee abduction moment on its own could not signify the complexity of the multi-planar loading experienced in dynamic tasks (Robinson, Donnelly, Vanrenterghem, & Pataky, 2015; Robinson, Sharir, Vanrenterghem, & Donnelly, 2017). Future studies should explore the capability of this new task-invariant approach by exploring the use of multi-planar knee loading to identify an individual's characteristics across tasks as it may give us clearer identification of at-risk behaviours.

## 5.5 Conclusions

Injury screening continues to present a significant challenge in identifying risk factors for an ACL injury as ranking inconsistency was seen across different tasks for all observed risk factors. From the existing risk factors, KAA at initial contact provided the highest correlation across tasks providing most task-invariant information for an individual's ACL movement signature but, the specific time at which the KAA was taken was similar for all tasks and does not provide information about subsequent loading during contact nor did it provide us with the risk factor's inter-quintile changes within the ranks. Further analysis observed that individuals have a systematic pattern of movement across multiple tasks that proves the existence of individual movement signatures. As more than half of the individuals identified with a movement signature were highly ranked, this may well infer at-risk classification thus, could provide a more enhanced and better-informed injury screening for researchers and practitioners.

# CHAPTER 6

## Can multi-planar variables rank individuals more consistently across tasks than uni-planar variables?

*The previous chapter found most prospective risk factors were not task-invariant, yet individual task-invariant movement signatures did exist. In this chapter, mechanism-informed multi-planar variables are explored to examine if they rank individuals more consistently than uni-planar variables.*

## 6.0 Abstract

The ACL injury mechanism is well-known to take place across multiple planes, yet rarely are multi-planar variables examined in an injury risk context. The purpose of this study was to determine if multi-planar loading variables rank individuals more consistently across multiple tasks than uni-planar loading variables. Forty-four female and forty-six male athletes regularly participating in dynamic sports took part in a controlled laboratory study. Five trials of bilateral drop vertical jumps (BDVJ), single-leg hops (SLHOP), single-leg drop vertical jumps (SLDVJ) and sidestep (SS) tasks were performed. Multi-planar and uni-planar variables of the knee, hip and ground reaction forces were extracted and correlated between tasks. Each participant's group was ranked according to each risk factor, and then grouped into quintiles for each task. Rank score and absolute sum of error for each participant's group were also calculated. Cohort analysis revealed most of the multi-planar and uni-planar variables to be poorly correlated. Individual analysis revealed 56 movement signatures identified out of the 90 participants and more than half of the movement signatures identified were highly ranked. Uni-planar movement signatures in the knee were identified more than the multi-planar movement signature for both sexes. Though sex-specific distribution was seen for the hip, where multi-planar movement signatures were identified more in females, which was the opposite in males. Therefore, multi-planar and uni-planar variables could both be considered when screening for at-risk behaviours.

## 6.1 Introduction

The anterior cruciate ligament (ACL) injury mechanism is well documented to involve combinations of undesirable multi-planar forces and kinematics during dynamic activities (Boden et al., 2000; Fauno & Wulff Jakobsen, 2006). Section 2.3 of this thesis describes how *in vitro*, *in silico* and *in vivo* biomechanical studies have demonstrated that greater magnitudes of ACL strain come from combinations of forces applied to the knee rather than a single uni-planar force alone (Markolf et al., 1995; Shin et al., 2011). In fact, sagittal plane forces alone are unlikely to rupture the ACL (S. G. McLean, Huang, Su, & Van Den Bogert, 2004). Consideration of multi-planar force and loading is clearly important, yet rarely are multi-planar variables examined in an injury risk context.

The mechanism of a non-contact ACL injury typically does not solely occur in one plane (Quatman et al., 2010) but in a combination of planes (multi-planar). The compound joint of the knee, the tibiofemoral joint, moves in six degrees of freedom, 3 rotations and 3 translations, which allows for movement in the sagittal, frontal and transverse planes (Komdeur, Pollo, & Jackson, 2002; Woo, Debski, Withrow, & Janaushek, 1999). In fact, because of the knee joint morphology its motion is always a combined rotation and translation, in which the tibia slides anteriorly on the femur articular surface when the knee goes into an extended position, putting the ACL in a taut configuration. Extreme loading to the knee joint, particularly in combination with a nearly extended knee, could therefore rupture the ACL. Consequently, for a non-contact ACL injury to occur, the individual has typically put themselves into an undesirable position e.g. landing with a nearly extended knee (Beynnon & Fleming, 1998; DeMorat et al., 2004; Hashemi et al., 2011), at a time when there is high external loading across various degrees of freedom. Altogether, there is reason to believe that multi-planar observations are necessary when trying to investigate the multi-planar individual behaviours that may be associated with increased non-contact ACL injury risk.

No *in vivo* biomechanical prospective study has explored multi-planar variables as potential risk factors. Recent prospective studies have only proposed uni-planar variables such as the knee abduction moment, knee abduction angle, vertical ground reaction force and knee flexion angle (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017). The variable closest to being multi-planar would be medial knee displacement (Krosshaug et al., 2016) which measures the combination of hip internal rotation and knee flexion. In the study of Krosshaug et al. (2016) only the medial knee displacement was associated to an increased risk of ACL injury. Whilst knee positioning is relevant, the forces experienced are not accounted for. To our knowledge no study has examined multi-planar joint moments or ground reaction forces.

As chapter 5 showed that movement signatures exist, in uni-planar risk factors, it may be possible that a more mechanism-informed, multi-planar load variable might rank individuals more consistently and may lead to more insightful movement signatures. Furthermore, this may provide a better justification of an individual's movement pattern and the types of loads that are dominating the knee. The aim of this study was to determine if the multi-planar loading variables rank individuals more consistently across bilateral drop vertical jumps (BDVJ), single-leg drop vertical jumps (SLDVJ), single leg hops (SLHOP) and sidestep (SS) tasks than uni-planar loading variables. A similar approach is taken to Chapter 5, where both cohort specific correlations and individual movement signatures are explored.

## 6.2 Methods

### 6.2.1 Participants and experimental design

Forty-four female (mean ± SD: age, 22.1 ± 3.7 years; height, 163.9 ± 8.0 cm; mass, 64.0 ± 10.6 kg) and forty-six male (mean ± SD: age, 21.1 ± 3.4 years; height, 175.6 ± 8.6 cm; mass, 75.1 ± 12.1 kg) were observed. Complete description of the participants and experimental design were described in section 4.2.1 and 4.2.2. An additional three female participants were added to this study as their full biomechanical analysis became available at the time of data analysis in this study.

### 6.2.2 Dynamic Tasks

Participants performed bilateral drop vertical jumps (BDVJ), single-leg drop vertical jumps (SLDVJ), single-leg hops (SLHOP) and 45° sidestepping (SS). Full details of the dynamic tasks involved has been described in Chapter 4 (Section 4.2.3).

### 6.2.3 Biomechanical assessments of the dynamic tasks

Full details of the kinematics and kinetics assessment procedures and calculations are described in Chapters 4, 5 and elsewhere (Malfait et al., 2014; Vanrenterghem, Gormley, Robinson, & Lees, 2010). The peak external abduction knee and hip moments were obtained during the weight acceptance phase (Dempsey et al., 2007). Peak ground reaction force was taken between initial contact and the take-off phase. For the multi-planar loading, a resultant vector magnitude of the frontal and transverse plane moments, i.e. non-sagittal plane moment vector, was calculated for the knee ($KM_{nsag}$) and hip ($HM_{nsag}$); and a resultant was also calculated for the anterior-posterior and vertical components of the ground reaction forces, i.e. sagittal plane forces ($GRF_{sag}$). Peak resultant vectors for the multi-planar loading were obtained between initial contact and take-off. For comparison, uni-planar loading was also defined as the frontal plane (i) knee moment, KM-Y; (ii) hip moment, HM-Y and (iii) vertical ground reaction force (GRF-Z). Means and standard deviations were calculated across tasks. It should be noted that the KM-Y data in this study differ slightly versus chapter 5 due to the additional three female participants.

### 6.2.4 Statistical Analysis

All statistical analyses were performed using SPSS (23.0.0.2, SPSS Inc.,Chicago, Illinois, USA) for dominant leg. Mean values for each task were obtained and then correlated in task pairs using a Spearman's rank correlation coefficient ($\rho$) to assess the ranking differences between tasks. For each variable, paired tasks were separated by sex. Correlation coefficients were rated as very good (0.90 - 1.00), good (0.70 - 0.89), moderate (0.40 - 0.69), poor (0.20 - 0.39) or very poor (0.00 - 0.19) (Field, 2013). Variables were ranked into quintiles and rank scores and the absolute sum of error was calculated to observe the consistency of each participant's ranking across tasks. Further details describing the rank score, absolute sum of error and the definition of a movement signature can be found in Sections 5.2.4 and 5.2.5.

## 6.3 Results

The descriptive data shows that $KM_{nsag}$ was the highest in SS while KM-Y appears to be generally consistent across tasks (Table 6.1). For HM-Y, the highest peak loads can again be seen in SS. $GRF_{sag}$ and GRF-Z in BDVJ were smaller than in the single-legged tasks.

Table 6.1 Descriptive data of variables across different tasks in females (n=44) and males (n=46)

| Task | | KM-Y $Nm.kg^{-1}$ | $KM_{nsag}$ $Nm.kg^{-1}$ | HM-Y $Nm.kg^{-1}$ | $HM_{nsag}$ $Nm.kg^{-1}$ | GRF-Z $N.kg^{-1}$ | $GRF_{sag}$ $N.kg^{-1}$ |
|---|---|---|---|---|---|---|---|
| BDVJ | F | 0.42 ± 0.18 | 0.50 ± 0.16 | 0.49 ± 0.25 | 0.77 ± 0.22 | 1.74 ± 0.50 | 1.74 ± 0.50 |
| | M | 0.34 ± 0.20 | 0.52 ± 0.14 | 0.61 ± 025 | 0.82 ± 0.19 | 1.81 ± 0.51 | 1.82 ± 0.51 |
| SLDVJ | F | 0.44 ± 0.25 | 0.81 ± 0.27 | 0.41 ± 0.12 | 2.03 ± 0.58 | 3.68 ± 1.01 | 3.69 ± 1.01 |
| | M | 0.34 ± 0.18 | 0.92 ±0.29 | 0.48 ± 0.14 | 1.86 ± 0.45 | 3.43 ± 0.53 | 3.43 ± 0.53 |
| SLHOP | F | 0.30 ± 0.13 | 0.78 ± 0.25 | 0.32 ± 0.19 | 1.91 ± 0.46 | 2.98± 0.77 | 3.04 ± 0.78 |
| | M | 0.22 ± 0.16 | 0.91 ± 0.24 | 0.35 ± 0.20 | 1.85 ± 0.38 | 3.09 ± 0.60 | 3.11 ± 0.60 |
| SS | F | 0.50 ± 0.87 | 1.13 ± 0.86 | 0.83 ± 1.32 | 2.03 ± 1.18 | 3.15 ± 0.93 | 3.26 ± 0.96 |
| | M | 0.36 ± 0.72 | 1.38 ± 0.61 | 1.16 ± 0.80 | 2.10 ± 0.67 | 3.04 ± 0.39 | 3.16 ± 0.42 |

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; F, female; M, male. Values are reported as mean ± SD*

### 6.3.1 Correlations between tasks

Overall, females had more significant relationships than males across all tasks and variables. Most of the variables showed low to very low correlation and very few showed moderate and good correlation. In females, only two paired tasks were significantly correlated for $KM_{nsag}$, however all KM-Y were significantly correlated across tasks (Table 6.2). In males, only one significant relationship was seen for $KM_{nsag}$, and four for KM-Y. The highest correlation was seen in $KM_{nsag}$ for males in SLDVJ and SLHOP pair with spearman rho ($\rho$) of 0.73. Significant relationships were seen across all tasks for females $HM_{nsag}$, but only 2 were seen in males however; no significant relationship was seen in females for HM-Y, but 3 significant relationships were seen in males. A consistent moderate to good correlation was seen for all variables across SLDVJ and SLHOP pair in both female and male except for HM-Y ($\rho$ = 0.43 – 0.73). Most GRF-Z and $GRF_{sag}$ did not have significant relationships across tasks for both females and males except for BDVJ and SLDVJ, and SLDVJ and SLHOP task pairs, and SHOP and SS for females, and most of the GRF-Z and $GRF_{sag}$ displayed very poor to moderate correlation across tasks ($\rho$ = -0.01 - 0.54). The SLDVJ and SLHOP correlations were significant for both females and males across all variables except for female's HM-Y.

Table 6.2 Spearman rank correlation coefficients for the risk factors across different tasks pairs

| Spearman's rho | | KM-Y | | $KM_{nsag}$ | | HM-Y | | $HM_{nsag}$ | | GRF-Z | | $GRF_{sag}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | M | F | M | F | M | F | M | F | M | F | M |
| BDVJ - SLDVJ | Correlation Coefficient | 0.64** | 0.39** | 0.33* | 0.02 | 0.29 | 0.43** | 0.44** | 0.06 | 0.34* | 0.43** | 0.33* | 0.43** |
| | *P* value | 0.00 | 0.01 | 0.03 | 0.90 | 0.05 | 0.00 | 0.00 | 0.71 | 0.02 | 0.00 | 0.03 | 0.00 |
| BDVJ - SLHOP | Correlation Coefficient | 0.57** | 0.54** | -0.01 | -0.09 | 0.14 | 0.13 | 0.47** | 0.17 | 0.27 | 0.22 | 0.27 | 0.27 |
| | *P* value | 0.00 | 0.00 | 0.94 | 0.54 | 0.36 | 0.39 | 0.00 | 0.26 | 0.07 | 0.14 | 0.08 | 0.07 |
| BDVJ - SS | Correlation Coefficient | 0.37* | 0.29 | 0.11 | -0.18 | 0.15 | 0.14 | 0.34* | 0.10 | 0.21 | 0.00 | 0.23 | 0.07 |
| | *P* value | 0.01 | 0.05 | 0.46 | 0.22 | 0.32 | 0.35 | 0.02 | 0.50 | 0.17 | 0.98 | 0.14 | 0.66 |
| SLDVJ - SLHOP | Correlation Coefficient | 0.62** | 0.50** | 0.55** | 0.73** | 0.28 | 0.35* | 0.70** | 0.64** | 0.43** | 0.50** | 0.44** | 0.54** |
| | *P* value | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SLDVJ - SS | Correlation Coefficient | 0.57** | 0.06 | 0.05 | 0.39 | 0.22 | 0.40** | 0.39** | 0.30* | 0.14 | -0.01 | 0.12 | 0.07 |
| | *P* value | 0.00 | 0.72 | 0.76 | 0.01 | 0.14 | 0.01 | 0.01 | 0.04 | 0.37 | 0.96 | 0.42 | 0.64 |
| SLHOP - SS | Correlation Coefficient | 0.50** | 0.40** | 0.14 | 0.34 | -0.11 | 0.10 | 0.51** | 0.23 | 0.32* | 0.00 | 0.29 | 0.01 |
| | *P* value | 0.00 | 0.01 | 0.36 | 0.02 | 0.47 | 0.50 | 0.00 | 0.12 | 0.03 | 0.96 | 0.06 | 0.99 |

* Colour chart

| r value | 0.00 to 0.19 | 0.20 to 0.39 | 0.40 to 0.69 | 0.70 to 0.89 | 0.90 to 1.00 |
|---|---|---|---|---|---|

***Correlation is significant at the 0.01 level (2-tailed).*

**Correlation is significant at the 0.05 level (2-tailed).*

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load; BDVJ, bilateral drop vertical jump; SLDVJ, single-leg drop vertical jump; SLHOP, single-leg hop; SS, sidestep; F, female; M, male*

### 6.3.2 Quintiles: Rank score and Absolute sum of error

A distinct pattern can be seen between the female and male quintile colour-maps (Figure 6.1). In females, the KM-Y rank scores had the highest number of participants who remained in the same quintile rank across tasks (2 in 5$^{th}$ quintile, 1 in 4$^{th}$ quintile and 1 in 1$^{st}$ quintile) and only one participant had $KM_{nsag}$ in quintile 5 for all tasks (Table 6.3). Only one participant with a HM-Y movement signature and one with a $HM_{nsag}$ remained in the same quintile across tasks for females. GRF-Z and $GRF_{sag}$ for females had the same number of participants who remained in the same quintile. Overall, females had more participants who remained in 5$^{th}$ quintile (undesirable) compared to the rest of the quintiles (in females) indicating those with undesirable characteristics likely continue these across tasks.

Overall, males had less participants who remained in the same quintile rank across tasks compared to females. KM-Y only had one participant in 4$^{th}$ quintile and two in the 1$^{st}$ quintile while only one of each (5$^{th}$ and 3$^{rd}$ quintile) was seen for male's $KM_{nsag}$. HM-Y had one participant in the 5$^{th}$ quintile, one in 2$^{nd}$ quintile and one in 1$^{st}$ quintile however, no participant remained in the same quintile rank for $HM_{nsag}$ as well as GRF-Z. Only one participant was seen in $GRF_{sag}$.

The lowest median-error line of the absolute sum of error was seen in KM-Y for both female and male (Figure 6.1 c,d) illustrating the highest number of participants who had less inter-quintile rank changes, 33 out of 44 for females and 31 out of 46 for males (Table 6.4). $HM_{nsag}$ in females has more participants above the median-error line than HM-Y. While not much differences was seen in males for the HM-Y and $HM_{nsag}$. GRF-Z for both female and male seems to have almost a similar number of participant changing groups compared to $GRF_{sag}$.

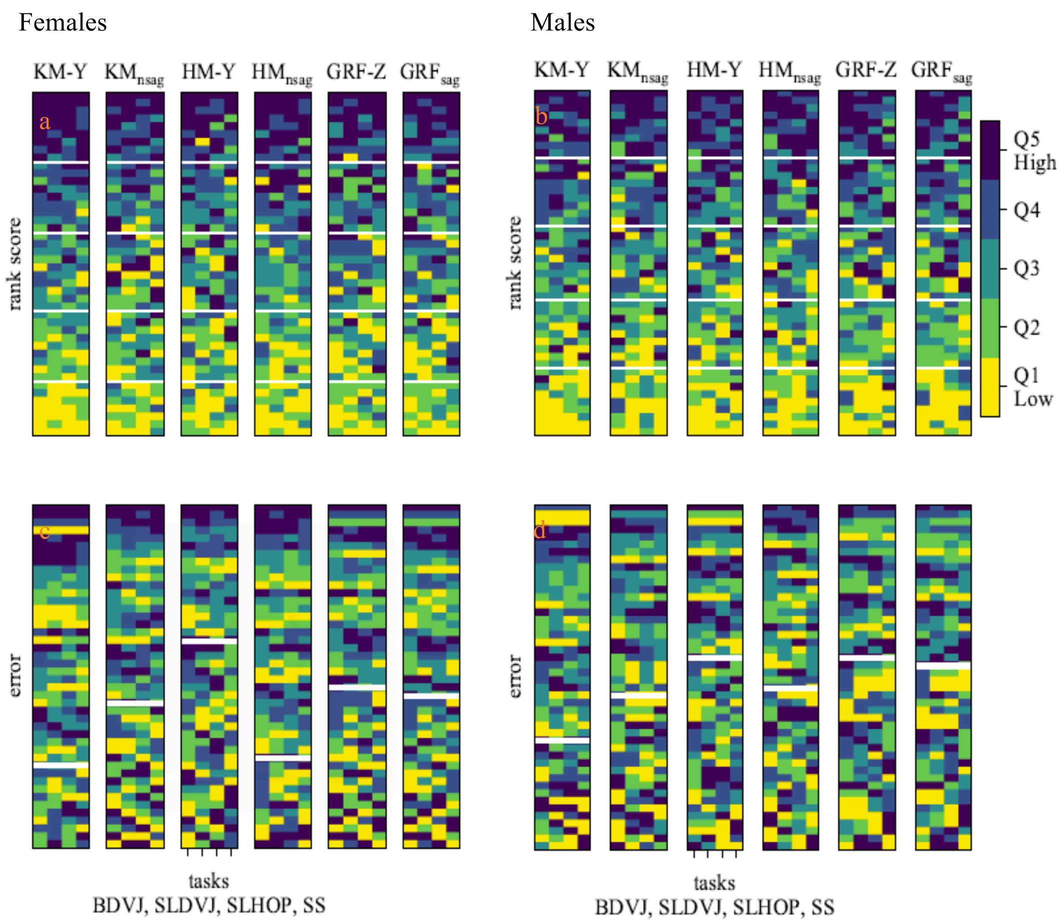



Figure 6.1 The quintile colour-maps illustrating summed rank score by quintile (a,b) and absolute sum of error (c,d) for female and males. The median-error of the absolute sum of error score was annotated onto each of the absolute sum of error column (white line).

Table 6.3 Number of participants who remained in the same quintile rank across all tasks

| n = 44<br>Quintiles / Variables | Female<br>Q5 High (n=8) | Q4 (n=9) | Q3 (n=9) | Q2 (n=9) | Q1 Low (n=9) |
|---|---|---|---|---|---|
| KM-Y | 2 | 1 | 0 | 0 | 1 |
| $KM_{nsag}$ | 1 | 0 | 0 | 0 | 0 |
| HM-Y | 1 | 0 | 0 | 0 | 0 |
| $HM_{nsag}$ | 1 | 0 | 0 | 0 | 0 |
| GRF-Z | 1 | 1 | 0 | 1 | 0 |
| $GRF_{sag}$ | 1 | 1 | 0 | 1 | 0 |

| n = 46<br>Quintiles / Variables | Male<br>Q5 High (n=9) | Q4 (n=9) | Q3 (n=10) | Q2 (n=9) | Q1 Low (n=9) |
|---|---|---|---|---|---|
| KM-Y | 0 | 1 | 0 | 0 | 2 |
| $KM_{nsag}$ | 1 | 0 | 1 | 0 | 0 |
| HM-Y | 1 | 0 | 0 | 1 | 1 |
| $HM_{nsag}$ | 0 | 0 | 0 | 0 | 0 |
| GRF-Z | 0 | 0 | 0 | 0 | 0 |
| $GRF_{sag}$ | 0 | 0 | 0 | 0 | 1 |

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load.*

Table 6.4 Number of participants above the absolute sum of error median-error line.

| | Female (n=44) | Male (n=46) |
|---|---|---|
| KM-Y | 33 | 31 |
| $KM_{nsag}$ | 25 | 25 |
| HM-Y | 17 | 20 |
| $HM_{nsag}$ | 32 | 24 |
| GRF-Z | 23 | 20 |
| $GRF_{sag}$ | 24 | 21 |

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load.*

### 6.3.3 Movement Signatures

Task-invariant movement signatures were observed; out of the total number of participant and risk factors per participants (n=540), 92 individual movement signatures were seen (Table 6.5). When sorted across participants, both sexes displayed very diverse pattern (Figure 6.2).

In females, most movement signatures seen at the knee were uni-planar (KM-Y), but at the hip, most movement signatures were multi-planar ($HM_{nsag}$). In males, little difference existed between multi-planar and uni-planar knee moment movement signatures but in the hip, substantially fewer (2 vs 7) multi-planar vs. uni-planar movement signatures were observed, this is of considerable contrast to the females. The $GRF_{sag}$ for both female and male had a slightly higher number of identified movement signature compared to GRF-Z.

Table 6.5 Total number of participants identified with movement signatures across tasks

| | Female<br>n = 44 | Male<br>n = 46 |
|---|---|---|
| KM-Y | 16 | 9 |
| $KM_{nsag}$ | 6 | 8 |
| HM-Y | 5 | 7 |
| $HM_{nsag}$ | 11 | 2 |
| GRF-Z | 7 | 5 |
| $GRF_{sag}$ | 9 | 7 |
| Total | 54 | 38 |

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load.*

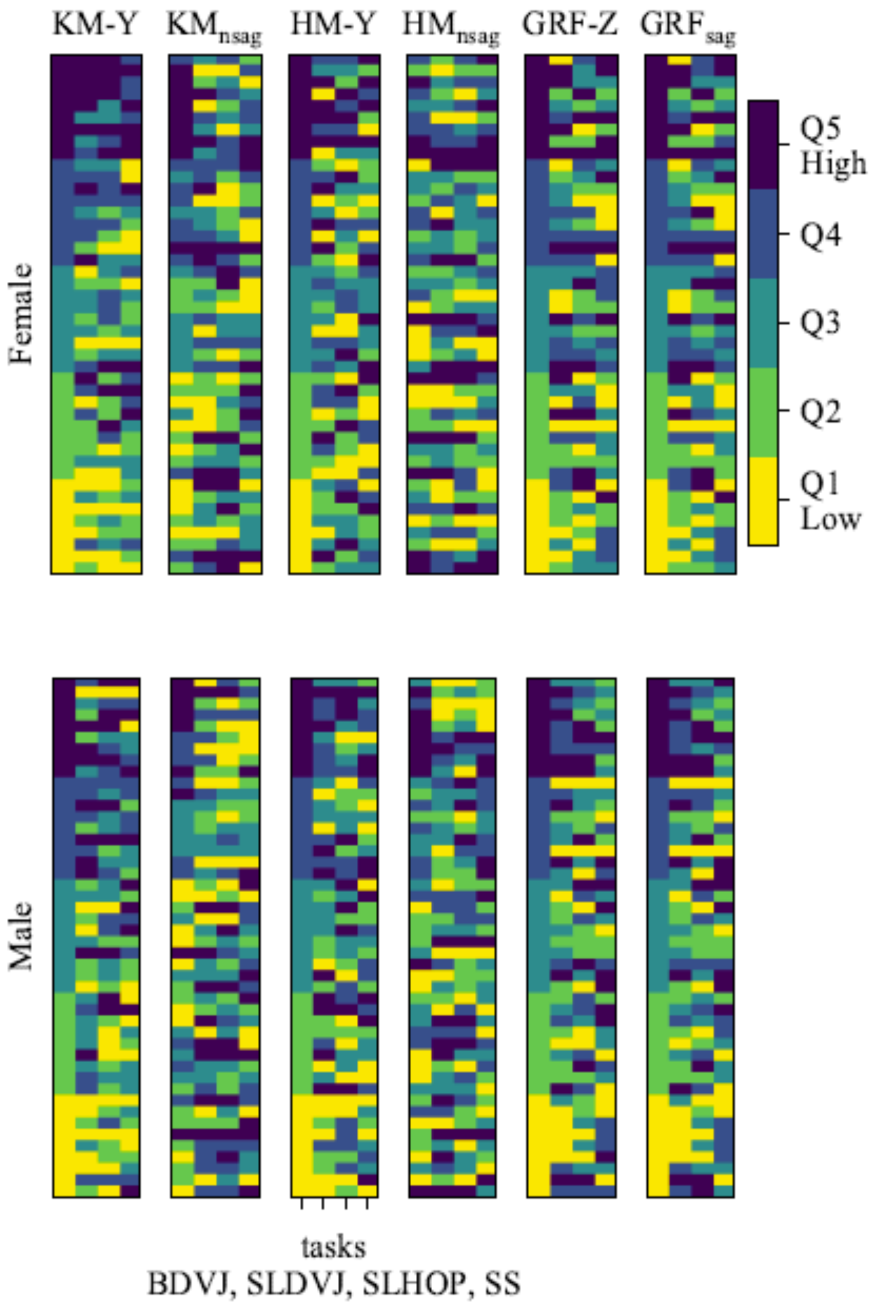



Figure 6.2 From left to right, each row's quintile colour-map were sorted across participants to illustrate how participants ranked across all risk factors and tasks

29 out of 44 females and 27 out of 46 males were identified with at least one variable's movement signature (Table 6.6). Nineteen unique movement signatures were identified across all participants illustrating the different combination of variables' movement signature that a participant have.

Table 6.6 Total number of unique movement signatures identified across overall participant rank scores for all tasks and variables

| Unique Movement Signatures | F | M |
|---|---|---|
| $GRF_{sag}$ | | 2 |
| GRF-Z | | 1 |
| GRF-Z, $GRF_{sag}$ | 3 | 4 |
| HM-Y | 1 | 3 |
| HM-Y, $GRF_{sag}$ | | 1 |
| HM-Y, GRF-Z, $GRF_{sag}$ | 1 | |
| HM-Y, $HM_{nsag}$ | 1 | |
| $HM_{nsag}$ | 3 | 2 |
| KM-Y | 6 | 4 |
| KM-Y, $GRF_{sag}$ | 1 | |
| KM-Y, GRF-Z, $GRF_{sag}$ | 2 | |
| KM-Y, HM-Y | 1 | 2 |
| KM-Y, $HM_{nsag}$ | 4 | |
| KM-Y, $KM_{nsag}$ | | 3 |
| KM-Y, $KM_{nsag}$, $HM_{nsag}$ | 1 | |
| $KM_{nsag}$ | 2 | 3 |
| $KM_{nsag}$, $GRF_{sag}$ | 1 | |
| $KM_{nsag}$, HM-Y | 1 | 2 |
| $KM_{nsag}$, $HM_{nsag}$, GRF-Z, $GRF_{sag}$ | 1 | |
| Total number of unique movement signatures = 19 | 29 | 27 |

*KM, knee moment; HM, hip moment; GRF, ground reaction force; Y, frontal uni-planar load; Z, vertical force; nsag/sag, multi-planar load.*

### 6.3.4 Highly ranked movement signatures

18 out of 29 female and 16 out of 27 male with unique movement signatures were highly ranked ($4^{th}$ and $5^{th}$ quintile) (Table 6.7). None of the females with high ranked KM-Y movement signature (7 out of the 16 KM-Y movement signatures identified) also had a high ranked $KM_{nsag}$ movement signature. Of the 6 $KM_{nsag}$ movement signatures identified, all except for one who ranked $3^{rd}$ quintile in females were undesirable. At the knee, males had 6 KM-Y movement signatures although 3 individuals had $KM_{nsag}$ movement signatures independent of KM-Y. Undesirable $HM_{nsag}$ movement signatures in females (6) were

identified more frequently than HM-Y. Though in males, only two undesirable HM-Y and $HM_{nsag}$ were identified. Four highly ranked GRF-Z and $GRF_{sag}$ movement signatures were identified together in females though one $GRF_{sag}$ was identified on its own while only one combination of highly ranked GRF-Z and $GRF_{sag}$ was seen in males. None of the male participants had a combination of uni-planar and multi-planar movement signatures for the knee and hip moments. Movement signatures were most evident for uni-planar knee moments in both females and males; yet movement signatures for hip moments were seen more frequently for uni-planar hip moments in males, and for multi-planar hip moments in females.

Table 6.7 The table below illustrates each participant's unique movement signatures and its quintile rank. Different colour blocks represent different movement signature rankings.

| F | KM-Y | $KM_{nsag}$ | HM-Y | $HM_{nsag}$ | GRF-Z | $GRF_{sag}$ |
|---|---|---|---|---|---|---|
| 1 | 5th | | | | | |
| 2 | | | | | 3rd | 3rd |
| 3 | | | 3rd | 3rd | | |
| 4 | 1st | | | 5th | | |
| 5 | | 4th | | | | 5th |
| 6 | | | | 2nd | | |
| 7 | | | | 4th | | |
| 8 | 5th | | 3rd | | | |
| 9 | 3rd | | | | | |
| 10 | 5th | | | | | |
| 11 | | 3rd | | | | |
| 12 | 3rd | | | | 1st | 1st |
| 13 | 5th | | | 5th | | |
| 14 | 4th | | | 1st | | |
| 15 | | 4th | | | | |
| 16 | 3rd | | | | | 3rd |
| 17 | | | 4th | | | |
| 18 | 1st | | | | | |
| 19 | 2nd | | | 3rd | | |
| 20 | 3rd | | | | | |
| 21 | | | | | 5th | 5th |
| 22 | | | 5th | | 4th | 4th |
| 23 | 5th | | | | 5th | 5th |
| 24 | 1st | 5th | | 4th | | |
| 25 | 1st | | | 5th | | |
| 26 | | | | 2nd | | |
| 27 | | | | | 2nd | 2nd |
| 28 | | 5th | 5th | | | |
| 29 | | 5th | | 5th | 5th | 5th |
| 30 | 5th | | | | | |

| M | KM-Y | $KM_{nsag}$ | HM-Y | $HM_{nsag}$ | GRF-Z | $GRF_{sag}$ |
|---|---|---|---|---|---|---|
| 1 | 1st | | 1st | | | |
| 2 | 4th | | | | | |
| 3 | 4th | | | | | |
| 4 | | | | | 4th | |
| 5 | | | | 4th | | |
| 6 | | | | | 5th | 5th |
| 7 | 3rd | 1st | | | | |
| 8 | 4th | | | | | |
| 9 | 5th | | 5th | | | |
| 10 | | 5th | | | | |
| 11 | | | | | 2nd | 2nd |
| 12 | | | 2nd | | | |
| 13 | 1st | 5th | | | | |
| 14 | | | | | | 4th |
| 15 | | 3rd | 3rd | | | |
| 16 | | 4th | 3rd | | | |
| 17 | | | | | 2nd | 2nd |
| 18 | | | | | | 4th |
| 19 | 5th | 3rd | | | | |
| 20 | | 3rd | | | | |
| 21 | | | | 5th | | |
| 22 | 5th | | | | | |
| 23 | | 3rd | | | | |
| 24 | | | | | 1st | 1st |
| 25 | | | 4th | | | 2nd |
| 26 | | | 1st | | | |

* Quintile rank colour

| 1st (Low) | 2nd | 3rd | 4th | 5th (High) |
|---|---|---|---|---|
| yellow | green | teal | blue | purple |

## 6.4 Discussion

This study aimed to determine if multi-planar loading variables rank individuals more consistently than uni-planar loading variables across bilateral drop vertical jumps (BDVJ), single-leg drop vertical jumps (SLDVJ), single leg hops (SLHOP) and sidestep (SS) tasks. $HM_{nsag}$ and KM-Y were significantly correlated across all tasks but otherwise at a cohort level, there were few significant relationships. At the individual level however, the SLDVJ and SLHOP pair was to consistently rank individuals with moderate to good correlation, as seen in Chapter 5 for uni-planar variables, except this time for HM-Y. When individual movement signatures were examined, several movement signatures were identified amongst the participants across all variables confirming that task-invariant movement signatures exist in multi-planar variables. There were distinct differences in movement signatures between sexes and in the distribution of uni-planar versus multi-planar movement signatures between the knee and hip. A large proportion of the movement signatures identified were ranked above the 4$^{th}$ quintile (undesirable) indicating that perhaps, task-invariant movement signatures could effectively indicate high-risk individuals while screening for ACL injury.

### 6.4.1 Correlational results: Cohort analysis

The poor correlations revealed that correlational analysis across individuals does not suggest task-invariance. The inconsistent behaviour of the uni-planar and multi-directional variables may perhaps be very much task-dependent. $HM_{nsag}$ and KM-Y in females was seen to correlate significantly across all tasks however only a few were significant for males. KM-Y in females has been extensively reviewed to be greater than in males in various high-risk dynamic tasks (Carson & Ford, 2011). Though, multi-planar variables have not been studied before, the significant correlations seen in $HM_{nsag}$ (Table 6.2) could be an indication that perhaps females may have different frontal and transverse hip moments than males which independently, had been observed in previous studies (Hart, Garrison, Palmieri-Smith, Kerrigan, & Ingersoll, 2008; Hewett, Ford, Myer, Wanstrath, & Scheper, 2006; Pollard, Sigward, & Powers, 2007).

The very poor to poor correlation seen in $GRF_{sag}$ in this present study was not unusual, as the anterior-posterior reaction forces are typically small (Munro, Miller, & Fuglevand, 1987). The small anterior-posterior forces would not change much to GRF-Z, keeping the poor relationship as seen in GRF-Z (Table 6.2).

Similar to Chapter 5, the SLDVJ and SLHOP pair also had a consistent ranking across multi-planar variables. This further justifies that tasks with movement similarities could translate not only in uni-planar variables, but multi-planar as well however, between these tasks, HM-Y was poorly correlated. When rank score and absolute sum of error was observed, HM-Y had the least number of participants who had fewer inter-quintile rank changes (Figure 6.1). Moreover, the higher task demand from SLDVJ which involves an explosive jump after landing from a 30cm box, could be the cause of a poorly correlated HM-Y. Therefore when compared to a more stable forward jump (SLHOP), it was expected that HM-Y would be larger in SLDVJ (Table 6.1). To our knowledge, no *in vivo* biomechanical studies have compared SLDVJ to SLHOP specifically. The closest investigation involving similar movements, demonstrated that a single-leg landing from a 20 cm height box produced higher loading compared to single-leg step-down or BLDVJ tasks (Harty et al., 2011). Peak hip adduction angles in single-leg landing were greater than in the other tasks, which describes the differences in hip motion of a more demanding task to a more stable single-leg landing task. Another study also supports this, where larger pVGRF was also seen in their single-legged drop landing task, though their task landed from a 45.7cm; which explains their high pVGRF values (Heebner et al., 2017). However, their forward jump to single-legged landing was seen to have the highest peak hip abduction angle compared to the other four tasks. This is perhaps due to the task not only involving a forward jump but also participants needing to clear an obstacle in front of them (Heebner et al., 2017). Differences in how the task is executed may influence the strength of the relationship.

### 6.4.2 Movement signatures: Individual Analysis

92 movement signatures were seen for both female and male across variables (n=540) which shows that certain multi-planar and uni-planar movement signature exist in some individuals (Table 6.5). The KM-Y movement signature (16 in females, 9 in males) was identified more than $KM_{nsag}$ movement signatures (6 in females, 8 in males) for both sexes. Interestingly, both uni-planar and multi-planar movement signatures identified did not correspond i.e. participant identified with $KM_{nsag}$ movement signature did not have KM-Y movement signature (Table 6.7). As a matter of fact, $KM_{nsag}$ and KM-Y movement signatures all came from different participants. A study by Robinson et al. (2017) has also observed a similar outcome where their at-risk participants identified by $KM_{nsag}$ were not identified by KM-Y and it was likely influenced by the magnitude from the transverse plane moment. This means, someone who has a KM-Y or HM-Y based movement signature may not necessarily have high transverse plane moments, therefore would not be identified as having a $KM_{nsag}$ or $HM_{nsag}$ movement signature. These differences may also explain why poor correlation was seen between multi-

planar and uni-planar variables in the spearman correlation table. This further justifies that uni-planar alone is unlikely to capture all individuals with undesirable movement signatures. Unique differences were also seen in the hip movement signatures. The $HM_{nsag}$ movement signature was identified more than HM-Y movement signature in females, though in contrast to their counterparts, males identified more HM-Y movement signatures. The hip moment signature differences between female and male is possibly due to the greater hip frontal and transverse plane movement observed in females, which could likely influence the higher number of $HM_{nsag}$ identified in females. Findings from Ford et al. (2006) and Mendiguchia, Ford, Quatman, Alentorn-Geli, and Hewett (2011) observed greater frontal and transverse plane hip movement in females compared to males. Though more investigation is needed to better inform this notion as lesser frontal and transverse plane hip movement and strength was seen in several studies between females and males (Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; McLean, Lipfert, & van den Bogert, 2004). Nonetheless, based on our previous chapter and as suggested by Harty et al. (2011), there may be some neuromuscular patterns that exist across tasks. Higher activity in the quadriceps and lower activity in the gluteal muscles contributed to poor hip control in females (Zazulak et al., 2005; Zeller, McCrory, Kibler, & Uhl, 2003). Combined with greater hip abduction, it causes the femur to internally rotate which leads the knee to a more abducted position than those of the male participants. The different neuromuscular activity in the frontal and transverse hip movements seen in females could play a role in the different movement signatures seen for hip moment.

### 6.4.3 Undesirable (high ranked) movement signatures

60.71% of the total unique movement signatures identified (n=56) ranked above the 4$^{th}$ quintile (Table 6.7). This indicates that the task-invariant movement signature could perhaps better inform ‘at-risk’ movement behaviours across tasks or at least within this study, participants with higher load (undesirable loading). The highly ranked (undesirable) uni-planar and multi-planar movement signatures were identified in different participants. Overall, this means that if individuals were consistent across tasks (movement signature), there is approximately a 1 in 2 chance that they would be highly ranked therefore, this further justifies the capability of a movement signature to detect undesirable behaviour.

As for ground reaction forces, 4 out of 5 of the highly ranked movement signatures in females, and 1 out of 3 highly ranked movement signatures in males, were identified with both $GRF_{sag}$ and GRF-Z. This is very much likely due to the anterior-posterior forces being typically small (Munro et al., 1987) consequently ranking both GRF-Z and $GRF_{sag}$ movement signature identically. This indicates that maybe multi-planar loading alone could be used to identify undesirable ground reaction forces.

This study provides preliminary evidence that both multi- planar and uni-planar movement signatures can contribute to identifying individuals at risk. It also provides a stronger indication that individuals exhibit task-invariant movement patterns across tasks. Not only that, this finding also indicates that task-invariant movement signature exist in multi-planar variables as well. When applied to injury screening, multi-planar task-invariant movement signatures may potentially identify behaviour-related at-risk individuals more effectively therefore providing a powerful tool in screening as it take the multi-planar aspect of ACL injury into account. As none of the multi-planar variables and concepts of screening at-risk individuals has been done before, its value should be tested in a prospective study.

## 6.5 Conclusions

When studying an entire cohort of recreational athletes, mostly poor correlations between variables across tasks were observed, in uni-planar as well as multi-planar variables. However, when looking within individuals; task-invariant movement signatures were seen not only in uni-planar variables but in multi-planar variables as well. Distinct differences in the distribution of uni-planar versus multi-planar movement signatures were seen in the knee for both sexes. Uni-planar movement signatures in the knee was identified more than the multi-planar movement signature for both sexes. Though sex-specific distribution was seen for the hip, where multi-planar movement signatures were identified more in females, which was the opposite in males. Both multi-planar and uni-planar variables should be considered when screening for injury as both of these variables are of importance in identifying at-risk movements. The majority of the total number of movement signatures identified as highly ranked demonstrates that task-invariant movement signatures better inform undesirable (at-risk) behaviours. This study has brought us closer to a better method of injury screening by understanding and appreciating the multi-planar commonalities that exist across tasks. Therefore, taking account of Donnelly et al. (2012)'s ACL injury prevention framework and as suggested in Bahr's (2016) critical review, the next step is to test this new approach prospectively using actual ACL injury data to see whether task-invariant movement signatures could better separate injured participants from non-injured (Stage 4 and 5 of Donnelly et al. (2012)'s injury prevention framework).

# CHAPTER 7

General Discussion

## 7.0 Summary

This thesis proposed to critically evaluate the biomechanical risk factors for non-contact ACL injury during dynamic sporting activity and to explore different approaches to evaluate existing risk factors through several objectives. The findings from this thesis revealed that; (i) only one *in vivo* biomechanics prospective cohort study can serve as a predictor of non-contact ACL injury. A scarcity of *in vivo* biomechanical risk factors for ACL injury were seen; however, a large number of level 2 and 3 evidence studies were available (Chapter 3); (ii) through cohort observations, most of the existing prospective risk factors for ACL injury displayed inconsistencies across tasks, while only knee abduction angle at initial contact provided the greatest consistency across tasks. Through individual observation, task-invariant movement signatures were identified in our cohort. The high number of movement signatures observed indicate that task-invariant movement signatures exist and were able to identify undesirable (at-risk) movement behaviour (Chapter 5); (iii) further exploration of multi-planar and uni-planar variables through cohort analysis showed mostly poor correlations across tasks. When observed at an individual level, task-invariant movement signatures also existed in multi-planar variables (Chapter 6). The novel approach of this thesis has brought us closer to a more enhanced method of injury screening across tasks by appreciating the commonalities and relationships that exist across tasks, which could lead to the development of novel evidence-informed injury screening and prevention programs.

## 7.1 An update on the systematic review

Since the systematic review searches were done (January 1990 - 10th August 2015), three more *in vivo* prospective studies on biomechanical risk factors for ACL injury were published (Krosshaug et al., 2016; Leppanen, Pasanen, Krosshaug, et al., 2017; Leppanen, Pasanen, Kujala, et al., 2017), and these studies all had in common that they were in conflict with the outcome of the only prospective study found through our systematic review (Hewett et al., 2005). One study (Krosshaug et al., 2016) purposely designed their prospective study to validate the results of Hewett et al., (2005). They initially found that out of the observed risk factors “medial knee displacement” could help distinguish injured participants from non-injured. However, they since published a Corrigendum (Krosshaug et al., 2017) in which these results were corrected based on the discovery of errors in their data processing, and subsequently none of the risk factors helped predict ACL injuries. Of the other prospective studies published in October 2016 and December 2017, also none found that any of Hewett et al.’s ACL injury predictors could predict injuries in their participants (Leppanen, Pasanen, Krosshaug, et al., 2017; Leppanen, Pasanen, Kujala, et al., 2017). First of all, these studies confirm that the critical take on the limited prospective evidence in our systematic review was justified, but secondly it suggests that a single dependent variable will unlikely be sufficient to predict non-contact ACL injuries.

As mentioned in Section 3.4.2, these conflicting results may have come from the inconsistent filtering of the motion and force data in Hewett et al.'s study as artefacts could have been introduced to their data as described by Kristianslund and Krosshaug (2013) in their study. The simple model used in Hewett et al.'s study may also contribute to the conflicting results as the quality of the interpretation of the biomechanical measurements are questionable especially with regards the determination of the hip joint centre and the dynamic tracking of segments. Krosshaug et al. (2016) measured the hip joint center by the anterior-posterior position of the greater trochanter marker (Bell, Pedersen, & Brand, 1990) while Leppanen, Pasanen, Krosshaug, et al., 2017 and Leppanen, Pasanen, Kujala, et al., 2017 determined their hip joint centres according to the Plug-in Gait model (Vicon Nexus v1.7). The different biomechanical modelling and analysis processes used could be one reason why the variables identified by Hewett et al. were not replicated in these latter studies.

Despite the rather discouraging outcome from these latest studies, conducting prospective studies is still the best way to strengthen the evidence on risk factors in the future, but there are many challenges with this type of study (Padua, 2010). In this thesis a prospective study was attempted (Chapter 4) but was unsuccessful in observing any ACL injuries. There are a number of issues with the way in which prospective studies are currently being conducted that deserve some further attention. One factor that stands out the most is the type of task used as all of the prospective studies have used a bilateral drop vertical jump (Krosshaug et al., 2007; Leppanen, Pasanen, Krosshaug, et al., 2017; Leppanen, Pasanen, Kujala, et al., 2017). It is well recognised that ACL injuries happen in single-legged stance and during situations involving sudden changes of direction, sudden deceleration, or landing from a jump (Alentorn-Geli et al., 2009; Boden et al., 2000; Sanna & O'Connor, 2008; Yu & Garrett, 2007). Gaining insights into how well players control their movement during such single legged highly dynamic tasks may well be unlikely to come from jumping off a box with both feet. Whilst a considerable amount of space (for running and change of direction) and a high-end 3D motion capture system may be one of the restrictions to using more applicable tasks, the use of a more sport-specific task might produce more sensitive and specific ACL injury predictors. In addition, as suggested in Chapter 3, moving towards a multi-centre approach would provide opportunities to increase the numbers of participants and consequently the number of observed injuries whilst minimizing methodological inconsistency (DiCesare et al., 2015; Donnelly et al., 2017). Altogether, such methodological considerations may have important implications for the prospective identification of the *in vivo* biomechanical risk factors for ACL injury.

Another relevant issue identified from the existing prospective studies is the characteristics of the participants observed in terms of age, sex, level of play, and fitness level. In Chapter 3 we observed that many of the associative studies with male participants used risk factors found in females for their studies. Since the systematic review, all of the subsequent prospective studies have also only observed female cohorts. Moreover, Krosshaug et al. (2016) argued that they had not confirmed the previous prospective predictive risk factors (Hewett et al., 2005) due to the age and level of play of their participants who were elite adult athletes. Even when the younger (15 years of average) female basketball and floorball junior league participants were matched more closely in terms of age and level of play, knee abduction moments or angles were not predictive of injury (Leppanen, Pasanen, Krosshaug, et al., 2017; Leppanen, Pasanen, Kujala, et al., 2017). As ACL injuries occur more often during competition than training (A. M. Joseph et al., 2013; Walden et al., 2011), risk factors could well be specific to sport, level of play, and competition (A. M. Joseph et al., 2013). ACL injury incidence rates are higher in late childhood i.e. aged 10~12 (Bjordal et al., 1997; Mall et al., 2014), and younger adolescents i.e. aged 13~18 (Caine et al., 2014; Gianotti et al., 2009; Shaw & Finch, 2017), compared to adults. Maturity status also appears to be relevant as immature males were more common to have an ACL injury (Prince, Laor, & Bean, 2005), whereas females were more prone after maturation (Fayad, Parellada, Parker, & Schweitzer, 2003). Different findings from different age groups of cohorts and with different maturation statuses could perhaps indicate an age-sensitivity where different age ranges may have different neuromuscular capabilities. As age, maturation and skill levels appear to be key factors identified for the frequency of injuries seen, this could be addressed by including a wider age range of athletes. To date, no prospective biomechanical studies have observed males, therefore predictive risk factors for males are still unknown. The absence of studies on biomechanical risk factors in males seems to have led to injury screenings and prevention programs to primarily emphasise on neuromuscular risk factors of the injury instead of biomechanical risk factors (Monajati et al., 2016). The sex differences identified for movement signatures in our studies (Chapter 5 and 6) and the sex differences seen in risk models (Beynnon et al., 2015) further justify that sex-specific risk factors (variables) are needed to effectively screen male participants and in order to do so, prospective studies to inform male-specific risk factors are warranted.

Existing prospective studies are informative, in the sense that they have shown us that conflicting results associated to ACL injury could be population-specific; or, injury risk factors are just different for everyone. Nonetheless, future studies should be aware of what is lacking from the previous published prospective studies if more successful biomechanical predictors are to be found. Though, if we strictly wait for the 'perfect' prospective study to come out or the ideal method to be recognised, then one may wonder how injury prevention can move forward without having the scientific evidence to build upon. Can progress still be achieved if we moved from evidence-based to evidence-informed screening and prevention? Essentially, evidence-informed practice comes about through expert judgement of one's experiences in the field added with key information that is provided from scientific knowledge. When dealing with athletes, practitioners intend to do what is best for the athlete based on their experiences within the context they work in. From collective experiences (and previous studies), the practitioner chooses the appropriate techniques or methods that he or she feels would work for specific athletes and attempts to stay up to date on new techniques or methods that become available. However, there is always a danger where practitioners ignore or overlook the reliability and validity of these tests/methods considering the commercial interest from product manufacturers and distributors. The lack of strong evidence that currently exists on the value of any biomechanical screening provides a wide-open playing field for product developers, with hardly any rules imposed through scientific evidence. So without high-quality prospective evidence, non-contact ACL injury screening and prevention will remain a contentious issue from which individuals with exclusively commercial interests - and to a much lesser extent our sporting population - will continue to benefit. Our recommendation in generating critical mass through prospective studies (Chapter 3) still stands and; considerations discussed in this chapter will hopefully help researchers focus their efforts.

## 7.2 A new perspective on movement screening

As discussed in Chapter 3 and Section 7.1, prospective studies on the biomechanical risk factors of non-contact ACL injury are limited and with conflicting results. Therefore, according to Bahr (2016)'s critical review, if one does not go through the exhaustive 3-step validation process where prospective studies play a big part in identifying and evaluating risk factors, it is quite possible that injury screening will never work. Whilst we are not disagreeing that a thorough validation should be done to achieve successful injury screening, our findings suggested that the reliance on one risk factor to be validated from a cohort, could be examined from a different approach.

Traditionally, once a risk factor has been determined, the general advice is to not translate this risk factor into different tasks or populations until it has been confirmed in an independent prospective study. Studies such as Krosshaug et al. (2016) and Leppanen, Pasanen, Kujala, et al. (2017) attempted to do this for a different population, i.e. age group and sport. An important commonality between these studies is that they utilized what we could call a "uni-variate" approach (page xiv), where unique risk factors are observed within one particular task (Figure 7.1). In this approach, the predictive strength of a parameter is quantified directly through its sensitivity and specificity for correctly identifying individuals as being at-risk or not. Another way of evaluating risk factors would be an "omni-variate" approach (page xiv). This approach involves the observation of several tasks and parameters in search of a risk profile rather than individual risk factors, which then requires machine learning or advanced statistical approaches (Hastie, Tibshirani, & Friedman, 2009). Multiple parameters of interest from different tasks are fed into a search algorithm to identify which (combination of) parameters are more meaningful than others in predicting an injury (Bittencourt, Ocarino, Mendonca, Hewett, & Fonseca, 2012). An immediate limitation of this approach, however, is that omni-variate risk involves sophisticated machine learning capabilities which is not typically available to most practitioners. More so, the outcome of such analysis is a complicated risk profile that is based on the common patterns within an entire population, but which still remains difficult to use at an individual level.

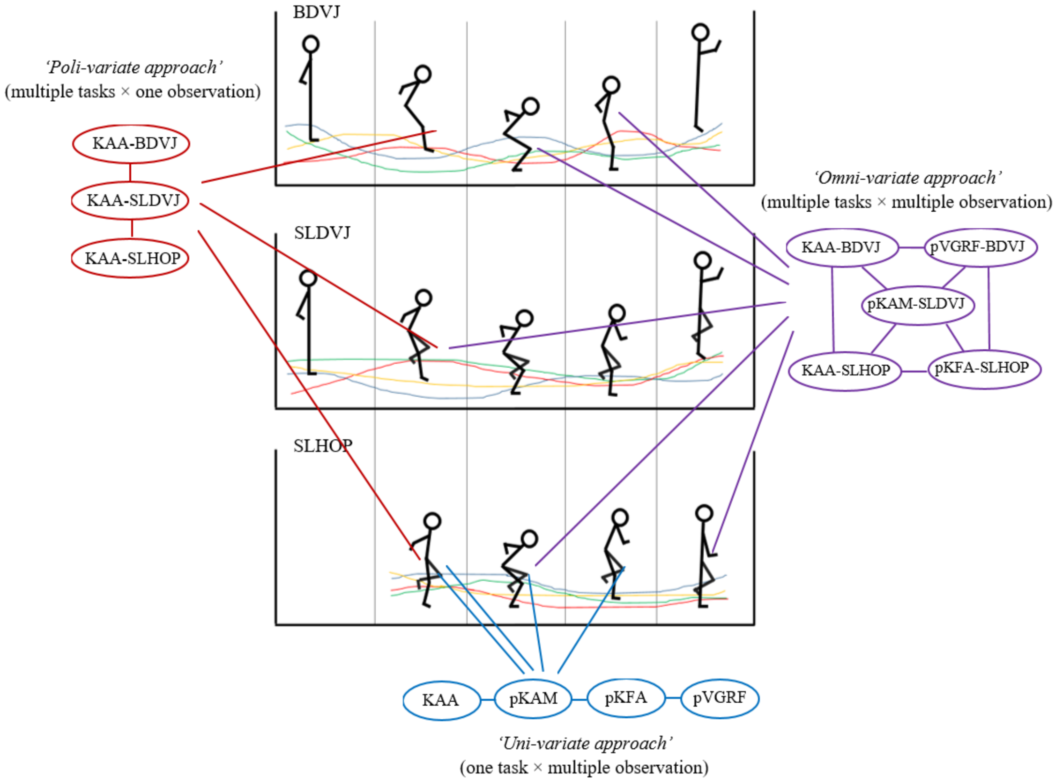



Figure 7.1 A visualisation of the "uni-variate", "poli-variate", and "omni-variate" approaches for observing non-contact ACL injury risk.

Through our work we have identified an intermediate approach, which we have termed the "poli-variate" approach (page xiv). In this approach, one risk factor/parameter is observed across multiple tasks. This approach is based on the premise that if an individual has an underlying movement behaviour (which may be a neuromuscular strategy), then that behaviour would probably reflect across different movement tasks. Individuals with their own movement patterns could be recognisable across different tasks. In this way, individuals having task-invariant risk factors can reveal a "movement signature" – a collection of variables characterising an individual's at-risk behaviour across tasks. Considering that the individual is evaluated several times across a number of tasks, this means that the level of certainty about injury risk is increased, or in other words, that the false positive rate from a uni-variate approach can be decreased. Importantly, this approach translates into a screening modality that can directly improve injury risk calculation at an individual level, which strengthens its use not only for risk factor determination but also for screening purposes. Through the work described in this thesis we believe to have demonstrated the potential of this new approach, and in order for this new approach to be a success, further validation of movement signatures through prospective studies should be considered in future work.

## 7.3 Complexity of the signals/risk factors

Usually, risk factor identification as well as consequent injury screening is done in a uni-variate approach by observing uni-planar discrete variables, as seen in Chapter 3 and further discussed in Section 7.1. Therefore, relying on a screening tool that evaluates on observation of the probability of one variable i.e. peak knee abduction moment that was only found to be predictive in one prospective study would not be sufficient. It was not a surprise that screening tools involving predictive algorithms based on these uni-variate risk factors, e.g. the Lower Extremity Scoring System (LESS), did not find any significant relationship to injured individuals when further validated (Goetschius et al., 2012; Smith et al., 2012). The main reason for traditional uni-planar observations is likely a consequence of lack of methods to evaluate multi-dimensional variables, particularly from a statistical point of view. However, the recent introduction of analysis techniques such as Statistical Parametric Mapping (Pataky, 2010; Pataky, Robinson, & Vanrenterghem, 2016) and Principal Component Analysis (Federolf, Reid, Gilgien, Haugen, & Smith, 2014) into the field of biomechanics could open opportunities to explore multi-dimensional observations that are possibly better for discriminating between injured and non-injured populations in prospective studies. Observing multi-dimensional risk factors could lead us to a more task-invariant multi-factorial screening process and more suitably account for the complexity of non-contact ACL injury (Bittencourt et al., 2016).

Identifying movement signatures across tasks has indirectly proven their capability to observe sex-specific multi-planar risk factors. Chapter 6 identified sex-specific movement signatures for the hip, where multi-planar movement signatures were identified more in females, and uni-planar movement signature were seen more in males. Our findings was aligned with Beynnon et al. (2015)'s multivariate study as they also saw differences between sexes and suggested a sex-specific screening mechanism to be developed in order to effectively identify individuals at risk. Risk has predominately been tested in a uni-variate way (Beynnon et al., 2015). Similarly, biomechanical risk has been evaluated for 0-dimensional observations made in a single task. This may well be a shortcoming, as through screening one tends to make predictions about injury risk based on an individuals' generic performance of sporting tasks. As the complexity of non-contact ACL injury may come from many possible interactions and determinants (internal and external factors) and if these interactions were observed, it could better inform the occurrence of an injury (Bittencourt et al., 2016). This would require a multi-variate approach in which to consider the predictive strength of multiple observations combined. Moreover, multivariate analysis could identify risk factors that uni-variate may not be able to identify (Beynnon et al., 2015). In our case of observing multi-planar and uni-planar variables, this shows that by adding complexity and concentrating on sex-specific risk factors could help identify at-risk individuals. However, further investigations are needed in validating this approach to further confirm its effectiveness in identifying at-risk individuals.

## 7.4 Movement screening approach in risk profiling

Previous studies have suggested that some neuromuscular imbalances could be linked to ACL injury mechanism. Hewett, Ford, Hoogenboom, and Myer (2010) have suggested four neuromuscular profiles which could relate to each of the variables that from which movement signatures were identified in Chapters 5 and 6. Our findings from Chapter 5 and 6 show, however, that not necessarily everyone was identified with a highly ranked KAA movement signature, and that some might be highly ranked in pKFA, or a combination of pKAM and KAA. By observing multiple risk factors that represent an injury mechanism component, task-invariant movement signatures could help detect specific neuromuscular deficits/imbalances for which specific interventions could be targeted. For example, when individual B (see section 5.4.6) was identified with a highly ranked pKFA movement signature, it is most likely indicating that the individual has an underlying neuromuscular deficit that falls under the "quadriceps dominance" to which strengthening the posterior chain, i.e. hamstrings, would be beneficial. Relating our new approach to the neuromuscular deficit profiles can thus lead to an important advancement in individualised ACL injury prevention, once again justifying that further studies are needed to validate the value of this new poli-variate approach.

## 7.5 Implications for practitioners

The findings from this thesis suggest a number of practical implications for those who work in ACL injury prevention. These are described in the paragraphs below.

*Application of a task-invariant movement signature for injury screening*

Practitioners should at all times remain critical about the value of singular variables (risk factors) on their own to represent injury risk. Chapter 5 and 6 have shown that observing multiple risk factors across a number of tasks can provide novel insight into individual behaviour. In this thesis it has been suggested that screening with multiple risk factors and tasks in order to identify movement signatures may well be beneficial. The immediate downside for a real world implementation is that screening a large number of individuals with multiple tasks would in most cases be too time consuming. Nonetheless, a more practical solution to the identification of movement signatures could be achieved by a hierarchical screening process (see Figure 7.2). Instead of testing 4 tasks systematically, a hierarchical approach could start with two tasks, for example the bilateral drop vertical jump as the task with strongest existing knowledge base, and the single-legged drop vertical jump. Individuals who do not consistently rank in the 4th or 5th quintile in any of the risk factors would not need further screening tests. However, those few with highly ranked movement signatures would then perform the rest of the tasks. In this hierarchical implementation the use ranking as part of quintiles for the two remaining tasks would no longer be possible, but normative data (for example from our work in Chapter 5) could help classify individuals.

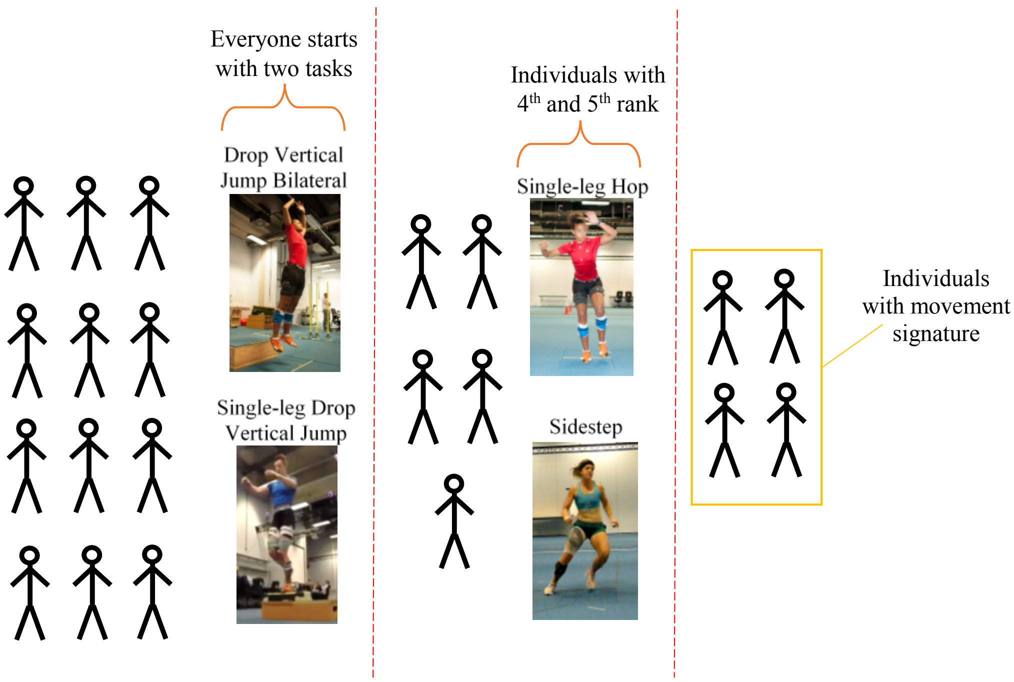



Figure 7.2 Implementation of hierarchical screening of the movement signature

*A robust method to evaluate the effectiveness of injury prevention programs*

The task-invariant approach introduced in Chapter 5 has the potential not only to strengthen screening, but also to be used as a method of evaluating the effectiveness of injury prevention programs. Typically, the effectiveness of an injury prevention program has been evaluated through a randomised control trial design, observing whether the prevention program results in a reduction of the incidence of injury in the intervention group compared to a control group. Nonetheless, this does not evaluate the direct impact of the intervention on the behaviour. Through the use of our poli-variate approach involving a movement signature evaluation, one could evaluate the athlete's task-invariant improvements on key risk factors, providing a more robust indication of the effectiveness of an intervention.

*Application of multi-planar variable for injury screening*

The findings from Chapter 6 may enable practitioners to identify at risk individuals which uni-planar variable alone could not identify. Injury screening with multi-planar variables may identify individuals who are behaving in a manner more closely associated to the ACL injury-mechanism however, findings from Chapter 6 shows that depending on the joint of interest i.e. hips or knees, both multi-planar and uni-planar variables were valuable. Previous ACL injury screening typically observe uni-planar parameters to assess whether an individual is at risk or not and perhaps this may not be sufficient.

## 7.5 Limitations

The studies in this thesis provide important insights into our understanding of biomechanical risk factors for non-contact ACL injury in dynamic sporting activities by critically reviewing the literature and by considering a new approach to overcome certain constraints of current screening approaches for non-contact ACL injury risk. Nonetheless, no studies are without limitations.

Our systematic review (Chapter 3) was specifically focused on the *in vivo* biomechanical studies. Though we acknowledge that other biomechanical research paradigms have made significant contributions to the understanding of ACL injury biomechanics including *in vitro* and *in silico* studies, it was our intention to focus on risk factors *in vivo* using participants of dynamic sports as these were most likely to inform injury prevention practice. However, non-biomechanical risk factors may also predict ACL injuries better than biomechanical risk factors alone, therefore a narrow focus on biomechanical factors only may not lead to a better injury prediction. Moreover, systematic reviews in general have the limitation that they reflect on what has been published. Knowing that a bias towards publishing significant results and positive findings exists (Dwan, Gamble, Williamson, Kirkham, & Reporting Bias, 2013), it means that there may have been more prospective studies which were not published. In fact, these could have provided a more balanced evidence base early on and avoided that the progression of this field of research has been rather biased towards the positive findings presented in the only published prospective study at the time (Hewett, 2005).

In this thesis, the focus was on biomechanical risk factors. As reviewed in Chapter 2, non-contact ACL injury is a multi-factorial phenomenon where many other factors will also influence risk and contribute to the injurious event, and where those other factors will in fact influence biomechanical risk. This is most obviously the case for neuromuscular risk factors, and particularly the ones associated to muscle activations. For example, increased activity in the quadriceps and reduced activity in the gluteal muscles has been shown to contribute to poor hip control (neuromuscular factor) but at the same time cause an abducted knee position (biomechanical factor) (Zazulak et al., 2005; Zeller et al., 2003). Multi-factorial observations were not possible within the scope of the work presented in this thesis, but could have given added value (Mok & Leow, 2016).

The risk factors used in Chapter 5 were the ones established at the time the study commenced. As discussed in Section 7.1, we acknowledge that there have been new developments on the availability of prospective evidence on biomechanical risk factors during the course of the work. The 'Corrigendum' for the prospective study by Krosshaug et al. (2016) also was published after the completion of the work in Chapter 5. A key consequence of that is that the selected risk factors in Chapter 5 came from the existing evidence at the time, which is now considered less supported. Added to that, in the available prospective evidence, only females were investigated. We did not have male prospective risk factors to work from and acknowledge that any conclusions that were made concerning males should have ideally been preceded by evidence from prospective studies.

Due to the lack of data to generate prospective evidence (Chapter 4), the findings from Chapter 5 and 6 are limited to the ranking of individuals against the population. The use of quintiles to stratify the sample does however, not give any absolute indication of the risk of injury of a population, let alone an individual within that population, as in theory all of the participants could be at high risk or low risk in reality. Considering that the injury incidence in our cohort was in fact lower than what would have been expected from epidemiological data, we could carefully assume that the overall injury risk of the population may well have been low, and ranking high within our population could still be a relatively low risk. Therefore, it might be worthwhile stressing that our analyses in Chapters 5 and 6 were primarily intended to explore new approaches concerning risk factor identification and injury screening, rather than to focus on any meaning of the absolute values of individuals within the cohort (e.g. the example individuals in section 6.2).

## 7.5 Future research/direction

Potential areas and recommendations for future research are outlined as below:

*Knowledge generation on non-contact ACL injury risk*

As described in Chapter 3, generating knowledge on injury risk may only be achieved by high-quality prospective studies. Therefore, the priority for research to advance the understanding of *in vivo* biomechanical risk factors for non-contact ACL injury is to produce critical mass of level 1 evidence studies however, these future prospective studies needs to cover the elements that has not been studied i.e. males, different tasks, wider age range as these will provide a more extensive and specific information regarding individual's risk factors. A broader target population could also inform and contribute greater impact on society as ACL injury does not only happen to elite athletes; whose cause of injury was seen due to their frequent high intensity match plays but also to recreational athletes whose injury could happen due to the lack of training and physical conditioning.

*Injury screening sensitivity/validation*

Future research on the sensitivity, reliability and validity of the task-invariant movement signature should be conducted on actual injury data or at-risk participants' data as this will ultimately determine its usefulness. Only when this approach has been tested out in the 'real-world' scenario or in multiple cohorts one will be able to evaluate how well the task-invariant movement signature can separate at-risk individuals from the crowd (Bahr, 2016; Donnelly et al., 2012). As addressed in section 7.3, movement signatures could potentially be used to develop and evaluate the effectiveness of individualized ACL injury prevention programs.

*Additional sport-like tasks/elements*

The tasks used to observe biomechanical risk factors in this thesis were limited to anticipated tasks, though ACL injuries often happen in unanticipated situations. Biomechanical differences are evident in unanticipated tasks such as larger peak knee abduction moments and angles (J. H. Kim et al., 2014). Future research could include tasks that are more sport-like, for example by task constraints that prevent the individual from pre-planning their movement (Almonroeder, Garcia, & Kurt, 2015). Similarly, observations could also be made in tasks that contain a stronger decision making component or a variation in focus of attention, knowing that there is likely a trade-off between cognitive load or external focus of attention and motor performance (Zachry, Wulf, Mercer, & Bezodis, 2005).

*Fatigue element*

Observing the element of fatigue in the lower limbs may add substantial information into ACL injury prevention as fatigue may contribute directly to the injury through faulty/high-risk movements. Increasing ACL injury incidence was observed towards the last 15 minutes of matches, which was likely an indication of increased level of fatigue (Ryynanen et al., 2013). Though, the neuromuscular control system can be influenced by either the central (brain) or peripheral (muscles) fatigue though investigations on the central fatigue are still scarce (Davis, 1995). Most high loading tasks which includes complex movements i.e. sudden change of direction or single leg landings, requires both central and peripheral fatiguing mechanisms (Borotikar, Newcomer, Koppes, & McLean, 2008). The inconsistent neuromuscular alterations in the lower limb that increases the risk of non-contact ACL injuries warrants for future research in injury screening as it could give us insights of how an individual would perform in an actual sport-like setting (Barber-Westin & Noyes, 2017).

*Observation of multi-planar variables in prospective studies*

As risk factors of non-contact ACL injury are typically observed through a singular plane of view, this perhaps could contribute to the conflicting results seen in previous prospective studies as ACL injury happens in different planes simultaneously however, no *in vivo* biomechanical prospective study has explored multi-planar variables as potential risk factors. Recent prospective studies have only proposed uni-planar variables such as the knee abduction moment, knee abduction angle, vertical ground reaction force and knee flexion angle (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen, Pasanen, Kujala, et al., 2017). Multi-planar kinematics and kinetics should be considered in future prospective studies as it can provide researchers with a more mechanism-informed injury risk factor. As explored in Chapter 6, it was possible to observe multi-planar variables. Further exploring these variables in prospective studies can provide researchers and practitioners with new insights into a better informed risk factors that represents actual injury mechanism.

*Incorporating innovative technologies for injury screening*

Several upcoming technological advances in the observation of motion can be found these days that do not require the need of an expensive 3D motion analysis system. One of these technological advances has become a major player in the industry of motion capture, namely the use of wearables and in particular inertial measurement units (IMU). These IMU's are miniature sensors that can produce kinematic and kinetic measurements that would enable researchers and practitioners to screen for injury not only in laboratory settings but also outdoors without the need for equipping the space with cameras. Some studies have used IMU as an injury prevention tool for shoulder injuries in overhead sports (Rawashdeh, Rafeldt, & Uhl, 2016) as well as a performance classification tool and musculoskeletal injury risk screening (Whelan et al., 2016). Though the validity and reliability of this technology would need investigation before it can be deemed effective for biomechanical injury screening. Future research could explore how wearables and markerless motion capture systems can contribute to the in-field implementation of biomechanical ACL injury screening.

*Other potential non-contact ACL injury risk factors*

Important future directions have been covered in previous sections, namely the exploration of multi-factorial approaches towards risk, though future research should also focus on other factors such as anatomical, hormonal, environment, footwear and genetics or in combination of these factors as it could provide us with better information regarding the complexity of the non-contact ACL injury. As mentioned by Beynnon et al. (2015) in their multivariate risk model study, measurements of multiple potential risk factors could lead to a more predictive evident of an individual with at-risk behaviours. Moreover, motor control and cognitive functions in particular could also contribute to the increased risk of ACL injury. A study has shown that individual with ACL injury had slower reaction time and processing speed compared to healthy controls as well as reduced scored on verbal and visual memory sections (Swanik, Covassin, Stearne, & Schatz, 2007). Combination of the neurocognitive function into non-contact ACL injury screening could potentially better inform us of not only the external but also the intrinsic risk factors of the debilitating injury.

*Multi-centre validation*

Efforts to move towards a multi-centre approach by conducting inter-laboratory reliability assessments and standardization of methods for injury screening could increase numbers of participants and observed injuries whilst reducing methodological inconsistency. Even though this type of research approach is still in its infancy, few studies has shown promising results as repeatability was obtained between testing centres (DiCesare et al., 2015; Donnelly et al., 2017). Therefore, if the new approach introduced in Chapter 5 and 6 could be implemented and validated through an inter-laboratory assessments, this can further strengthen the reliability and capability of the approach i.e. through increase numbers of participants and observed injuries whilst reducing methodological inconsistency.

# CHAPTER 8

Conclusion

The findings from this thesis has demonstrated that there is a scarcity of prospective studies on the biomechanical risk factors of ACL injury however; an increasing number on the level 2 and 3 evidence studies was also seen. In order to advance the understanding of *in vivo* biomechanical risk factors for non-contact ACL injury, generating critical mass of high quality level 1 evidence (prospective studies) should be a priority. The novel approach in injury screening introduced in this thesis – the task-invariant movement signature, has shown promising results in the ability to identify individuals with uni-planar movement signatures, which further indicates that individuals can have task-invariant patterns of movement. The ability of the movement signature to identify highly ranked individuals may well infer at-risk classification. Task-invariant movement signatures were also able to identify individuals with multi-planar variables. Nonetheless, the potential of this new approach still needs to be confirmed and validated with actual injury data. Essentially, the outcome of this thesis provides a better understanding of how one could work towards the development of more effective injury-screening tools, as well as more effective injury prevention programs. This will hopefully have an impact upon athletes and the general population in reducing the number of ACL injuries as well as being employed to enhance future studies investigating ACL injury risk.

# CHAPTER 9
References

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med, 33*(4), 524-530. doi:10.1177/0363546504269937

Agel, J., Evans, T. A., Dick, R., Putukian, M., & Marshall, S. W. (2007). Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train, 42*(2), 270-277.

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 Through 2012-2013). *Clin J Sport Med, 26*(6), 518-523. doi:10.1097/JSM.0000000000000290

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lazaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc, 17*(7), 705-729. doi:10.1007/s00167-009-0813-1

Almonroeder, T. G., Garcia, E., & Kurt, M. (2015). The Effects of Anticipation on the Mechanics of the Knee during Single-Leg Cutting Tasks: A Systematic Review. *Int J Sports Phys Ther, 10*(7), 918-928.

Arendt, E., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med, 23*(6), 694-701. doi:10.1177/036354659502300611

Bahr, R. (2016). Why screening tests to predict injury do not work-and probably never will...: a critical review. *Br J Sports Med, 50*(13), 776-780. doi:10.1136/bjsports-2016-096256

Baker, L. J. (2009). *Sex differences in kinematics and kinetics during a rotational jump landing and unanticipated cutting maneuver.* The University of Toledo,

Barber-Westin, S. D., & Noyes, F. R. (2017). Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training: A Systematic Review. *Am J Sports Med, 45*(14), 3388-3396. doi:10.1177/0363546517693846

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *J Biomech, 23*(6), 617-621.

Benjaminse, A., Habu, A., Sell, T. C., Abt, J. P., Fu, F. H., Myers, J. B., & Lephart, S. M. (2008). Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc, 16*(4), 400-407. doi:10.1007/s00167-007-0432-7

Berns, G. S., Hull, M. L., & Patterson, H. A. (1992). Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res, 10*(2), 167-176. doi:10.1002/jor.1100100203

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2001). External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc, 33*(7), 1168-1175.

Besier, T. F., Sturnieks, D. L., Alderson, J. A., Lloyd, D. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech, 36,* 1159–1168.

Beutler, A., de la Motte, S., Marshall, S., Padua, D., & Boden, B. (2009). Muscle Strength and Qualitative Jump-Landing Differences in Male and Female Military Cadets: The Jump-Acl Study. *J Sports Sci Med, 8*, 663-671.

Beynnon, B. D., & Fleming, B. C. (1998). Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech, 31*(6), 519-525.

Beynnon, B. D., Sturnick, D. R., Argentieri, E. C., Slauterbeck, J. R., Tourville, T. W., Shultz, S. J., & Vacek, P. M. (2015). A Sex-Stratified Multivariate Risk Factor Model for

Anterior Cruciate Ligament Injury. *J Athl Train, 50*(10), 1094-1096. doi:10.4085/1062-6050-50.10.05

Bicer, E. K., Lustig, S., Servien, E., Selmi, T. A., & Neyret, P. (2010). Current knowledge in the anatomy of the human anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc, 18*(8), 1075-1084. doi:10.1007/s00167-009-0993-8

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *J Biomech, 39*(13), 2438-2444. doi:10.1016/j.jbiomech.2005.07.021

Bittencourt, N. F., Meeuwisse, W. H., Mendonca, L. D., Nettel-Aguirre, A., Ocarino, J. M., & Fonseca, S. T. (2016). Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition-narrative review and new concept. *Br J Sports Med*. doi:10.1136/bjsports-2015-095850

Bittencourt, N. F., Ocarino, J. M., Mendonca, L. D., Hewett, T. E., & Fonseca, S. T. (2012). Foot and hip contributions to high frontal plane knee projection angle in athletes: a classification and regression tree approach. *J Orthop Sports Phys Ther, 42*(12), 996-1004. doi:10.2519/jospt.2012.4041

Bjordal, J. M., Arnly, F., Hannestad, B., & Strand, T. (1997). Epidemiology of anterior cruciate ligament injuries in soccer. *Am J Sports Med, 25*(3), 341-345. doi:10.1177/036354659702500312

Bjornaraa, J., & Di Fabio, R. P. (2011). Knee kinematics following acl reconstruction in females; the effect of vision on performance during a cutting task. *Int J Sports Phys Ther, 6*(4), 271-284.

Boden, B. P., Dean, G. S., Feagin, J. A., Jr., & Garrett, W. E., Jr. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578.

Boden, B. P., Sheehan, F. T., Torg, J. S., & Hewett, T. E. (2010). Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. *J Am Acad Orthop Surg, 18*(9), 520-527.

Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med, 37*(11), 2108-2116. doi:10.1177/0363546509337934

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon), 23*(1), 81-92. doi:10.1016/j.clinbiomech.2007.08.008

Braham, R., Finch, C. F., McIntosh, A., & McCrory, P. (2004). Community level Australian Football: a profile of injuries. *J Sci Med Sport, 7*(1), 96-105.

Brophy, R., Silvers, H. J., Gonzales, T., & Mandelbaum, B. R. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. *Br J Sports Med, 44*(10), 694-697. doi:10.1136/bjsm.2008.051243

Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *Br J Sports Med, 43*(13), 1049-1056. doi:10.1136/bjsm.2008.055954

Buller, L. T., Best, M. J., Baraga, M. G., & Kaplan, L. D. (2015). Trends in Anterior Cruciate Ligament Reconstruction in the United States. *Orthop J Sports Med, 3*(1), 2325967114563664. doi:10.1177/2325967114563664

Butler, D. L., Guan, Y., Kay, M. D., Cummings, J. F., Feder, S. M., & Levy, M. S. (1992). Location-dependent variations in the material properties of the anterior cruciate ligament. *J Biomech, 25*(5), 511-518.

Butler, D. L., Noyes, F. R., & Grood, E. S. (1980). Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am, 62*(2), 259-270.

Caine, D., Purcell, L., & Maffulli, N. (2014). The child and adolescent athlete: a review of three potentially serious injuries. *BMC Sports Sci Med Rehabil, 6*, 22. doi:10.1186/2052-1847-6-22

Carson, D. W., & Ford, K. R. (2011). Sex differences in knee abduction during landing: a systematic review. *Sports Health, 3*(4), 373-382. doi:10.1177/1941738111410180

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med, 30*(2), 261-267. doi:10.1177/03635465020300021901

Chaudhari, A. M., & Andriacchi, T. P. (2006). The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *J Biomech, 39*(2), 330-338. doi:10.1016/j.jbiomech.2004.11.013

Chmielewski, T. L., Rudolph, K. S., Fitzgerald, G. K., Axe, M. J., & Snyder-Mackler, L. (2001a). Biomechanical evidence supporting a differential response to acute ACL injury. *Clin Biomech (Bristol, Avon), 16*(7), 586-591.

Chmielewski, T. L., Rudolph, K. S., Fitzgerald, G. K., Axe, M. J., & Snyder-Mackler, L. (2001b). Biomechanical evidence supporting a differential response to acute ACL injury. *Clin Biomech, 16*(7), 586-591.

Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H., & McGivern, J. (2007). Characteristics of anterior cruciate ligament injuries in Australian football. *J Sci Med Sport, 10*(2), 96-104. doi:10.1016/j.jsams.2006.05.015

Corrigendum. (2017). *Am J Sports Med, 45*(9), NP28-NP29. doi:10.1177/0363546517716155

Cortes, N., Greska, E., Kollock, R., Ambegaonkar, J., & Onate, J. A. (2013). Changes in lower extremity biomechanics due to a short-term fatigue protocol. *J Athl Train, 48*(3), 306-313. doi:10.4085/1062-6050-48.2.03

Cortes, N., Greska, E., Kollock, R., & Onate, J. (2011). Sequential fatigue progressively alters lower extremity biomechanics. *British Journal of Sports Medicine, 45*(4), 340.

Cortes, N., Morrison, S., Van Lunen, B. L., & Onate, J. A. (2012). Landing technique affects knee loading and position during athletic tasks. *J Sci Med Sport, 15*(2), 175-181. doi:10.1016/j.jsams.2011.09.005

Cutting, J. E., & Kozlowski, L. T. (1977). Recognizing Friends by Their Walk - Gait Perception without Familiarity Cues. *Bulletin of the Psychonomic Society, 9*(5), 353-356. doi:Doi 10.3758/Bf03337021

Dallinga, J. M., Benjaminse, A., & Lemmink, K. A. (2012). Which Screening Tools Can Predict Injury to the Lower Extremities in Team Sports? *Sports Medicine, 42*(9), 791-815. doi:10.1007/bf03262295

Davis, J. M. (1995). Central and peripheral factors in fatigue. *J Sports Sci, 13 Spec No*, S49-53. doi:10.1080/02640419508732277

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Richard Steadman, J. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon), 18*(7), 662-669.

DeMorat, G., Weinhold, P., Blackburn, T., Chudik, S., & Garrett, W. (2004). Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med, 32*(2), 477-483. doi:10.1177/0363546503258928

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The effect of technique change on knee loads during sidestep cutting. *Med Sci Sports Exerc, 39*(10), 1765-1773. doi:10.1249/mss.0b013e31812f56d1

Dennis, R. J., Finch, C. F., Elliott, B. C., & Farhart, P. J. (2008). The reliability of musculoskeletal screening tests used in cricket. *Phys Ther Sport, 9*(1), 25-33. doi:10.1016/j.ptsp.2007.09.004

DiCesare, C. A., Bates, N. A., Barber Foss, K. D., Thomas, S. M., Wordeman, S. C., Sugimoto, D., . . . Myer, G. D. (2015). Reliability of 3-Dimensional Measures of Single-Leg Cross Drop Landing Across 3 Different Institutions: Implications for

Multicenter Biomechanical and Epidemiological Research on ACL Injury Prevention. *Orthop J Sports Med, 3*(12), 2325967115617905. doi:10.1177/2325967115617905

Donnelly, C. J., Elliott, B. C., Ackland, T. R., Doyle, T. L., Beiser, T. F., Finch, C. F., . . . Lloyd, D. G. (2012). An anterior cruciate ligament injury prevention framework: incorporating the recent evidence. *Res Sports Med, 20*(3-4), 239-262. doi:10.1080/15438627.2012.680989

Donnelly, C. J., Weir, G., Jackson, C., Alderson, J., Sharir, R., Rafeeuddin, R., . . . Robinson, M. (2017). *The inter-laboratory repeatability of unplanned sidestepping kinematics.* Paper presented at the International Society of Biomechanics in Sports, Colonge, Germany.

Duthon, V. B., Barea, C., Abrassart, S., Fasel, J. H., Fritschy, D., & Menetrey, J. (2006). Anatomy of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc, 14*(3), 204-213. doi:10.1007/s00167-005-0679-9

Dwan, K., Gamble, C., Williamson, P. R., Kirkham, J. J., & Reporting Bias, G. (2013). Systematic review of the empirical evidence of study publication bias and outcome reporting bias - an updated review. *PLoS One, 8*(7), e66844. doi:10.1371/journal.pone.0066844

Ekegren, C. L., Gabbe, B. J., & Finch, C. F. (2014). Injury reporting via SMS text messaging in community sport. *Inj Prev, 20*(4), 266-271. doi:10.1136/injuryprev-2013-041028

Ekegren, C. L., Miller, W. C., Celebrini, R. G., Eng, J. J., & Macintyre, D. L. (2009). Reliability and validity of observational risk screening in evaluating dynamic knee valgus. *J Orthop Sports Phys Ther, 39*(9), 665-674. doi:10.2519/jospt.2009.3004

Fauno, P., & Wulff Jakobsen, B. (2006). Mechanism of anterior cruciate ligament injuries in soccer. *Int J Sports Med, 27*(1), 75-79. doi:10.1055/s-2005-837485

Fayad, L. M., Parellada, J. A., Parker, L., & Schweitzer, M. E. (2003). MR imaging of anterior cruciate ligament tears: is there a gender gap? *Skeletal Radiol, 32*(11), 639-646. doi:10.1007/s00256-003-0694-1

Federolf, P., Reid, R., Gilgien, M., Haugen, P., & Smith, G. (2014). The application of principal component analysis to quantify technique in sports. *Scand J Med Sci Sports, 24*(3), 491-499. doi:10.1111/j.1600-0838.2012.01455.x

Field, A. P. (2013). *Discovering statistics using IBM SPSS : and sex and drugs and rock'n'roll* (4th ed. ed.). London: London : SAGE.

Filbay, S. R., Culvenor, A. G., Ackerman, I. N., Russell, T. G., & Crossley, K. M. (2015). Quality of life in anterior cruciate ligament-deficient individuals: a systematic review and meta-analysis. *Br J Sports Med, 49*(16), 1033-1041. doi:10.1136/bjsports-2015-094864

Finch, C. (2006). A new framework for research leading to sports injury prevention. *J Sci Med Sport, 9*(1-2), 3-9; discussion 10. doi:10.1016/j.jsams.2006.02.009

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech, 34*(2), 163-170.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc, 35*(10), 1745-1750. doi:10.1249/01.MSS.0000089346.85744.D9

Ford, K. R., Myer, G. D., Smith, R. L., Vianello, R. M., Seiwert, S. L., & Hewett, T. E. (2006). A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clin Biomech (Bristol, Avon), 21*(1), 33-40. doi:10.1016/j.clinbiomech.2005.08.010

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc, 37*(1), 124-129.

Ford, K. R., Shapiro, R., Myer, G. D., Van Den Bogert, A. J., & Hewett, T. E. (2010). Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc, 42*(10), 1923-1931. doi:10.1249/MSS.0b013e3181dc99b1

Fu, R. Z., & Lin, D. D. (2013). Surgical and Biomechanical Perspectives on Osteoarthritis and the ACL Deficient Knee: A Critical Review of the Literature. *Open Orthop J, 7*, 292-300. doi:10.2174/1874325001307010292

Gabbe, B. J., Bennell, K. L., Wajswelner, H., & Finch, C. F. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5*(2), 90-97. doi:10.1016/j.ptsp.2004.01.003

Gabr, A., De Medici, A., & Haddad, F. (2017). *The National Ligament Registry, The Third Annual Report (2017)*. Retrieved from http://www.uknlr.co.uk/

Gajic, O., Dabbagh, O., Park, P. K., Adesanya, A., Chang, S. Y., Hou, P., . . . Injury Trials Group: Lung Injury Prevention Study, I. (2011). Early identification of patients at risk of acute lung injury: evaluation of lung injury prediction score in a multicenter cohort study. *Am J Respir Crit Care Med, 183*(4), 462-470. doi:10.1164/rccm.201004-0549OC

Gehring, D., Melnyk, M., & Gollhofer, A. (2009). Gender and fatigue have influence on knee joint control strategies during landing. *Clin Biomech (Bristol, Avon), 24*(1), 82-87. doi:10.1016/j.clinbiomech.2008.07.005

Gerritsen, K. G., van den Bogert, A. J., & Nigg, B. M. (1995). Direct dynamics simulation of the impact phase in heel-toe running. *J Biomech, 28*(6), 661-668.

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. *J Sci Med Sport, 12*(6), 622-627. doi:10.1016/j.jsams.2008.07.005

Girgis, F. G., Marshall, J. L., & Monajem, A. (1975). The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. *Clin Orthop Relat Res*(106), 216-231.

Goerger, B. M., Marshall, S. W., Beutler, A. I., Blackburn, J. T., Wilckens, J. H., & Padua, D. A. (2015). Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: the JUMP-ACL study. *British Journal of Sports Medicine, 49*(3), 1-9.

Goerger, B. M., Marshall, S. W., Beutler, A. I., Blackburn, J. T., Wilckens, J. H., & Padua, D. A. (2015). Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: the JUMP-ACL study. *Br J Sports Med, 49*(3), 188-195. doi:10.1136/bjsports-2013-092982

Goetschius, J., Smith, H. C., Vacek, P. M., Holterman, L. A., Shultz, S. J., Tourville, T. W., . . . Beynnon, B. D. (2012). Application of a clinic-based algorithm as a tool to identify female athletes at risk for anterior cruciate ligament injury: a prospective cohort study with a nested, matched case-control analysis. *Am J Sports Med, 40*(9), 1978-1984. doi:10.1177/0363546512456972

Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., Lawrence, J. T., & Ganley, T. J. (2016). Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes: A Systematic Review and Meta-analysis. *Am J Sports Med, 44*(10), 2716-2723. doi:10.1177/0363546515617742

Greska, E. K., Cortes, N., Ringleb, S. I., Onate, J. A., & Van Lunen, B. L. (2017). Biomechanical differences related to leg dominance were not found during a cutting task. *Scand J Med Sci Sports, 27*(11), 1328-1336. doi:10.1111/sms.12776

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., . . . Wojtys, E. M. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg, 8*(3), 141-150.

Griffin, L. Y., Albohm, M. J., Arendt, E. A., Bahr, R., Beynnon, B. D., Demaio, M., . . . Yu, B. (2006). Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med, 34*(9), 1512-1532. doi:10.1177/0363546506286866

Grood, E. S., Noyes, F. R., Butler, D. L., & Suntay, W. J. (1981). Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am, 63*(8), 1257-1269.

Hanauer, D. A., Wentzell, K., Laffel, N., & Laffel, L. M. (2009). Computerized Automated Reminder Diabetes System (CARDS): e-mail and SMS cell phone text messaging reminders to support diabetes management. *Diabetes Technol Ther, 11*(2), 99-106. doi:10.1089/dia.2008.0022

Hart, J. M., Garrison, J. C., Palmieri-Smith, R., Kerrigan, D. C., & Ingersoll, C. D. (2008). Lower extremity joint moments of collegiate soccer players differ between genders during a forward jump. *J Sport Rehabil, 17*(2), 137-147.

Harty, C. M., DuPont, C. E., Chmielewski, T. L., & Mizner, R. L. (2011). Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks. *Scand J Med Sci Sports, 21*(1), 98-105. doi:10.1111/j.1600-0838.2009.01022.x

Hashemi, J., Breighner, R., Chandrashekar, N., Hardy, D. M., Chaudhari, A. M., Shultz, S. J., . . . Beynnon, B. D. (2011). Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. *J Biomech, 44*(4), 577-585. doi:10.1016/j.jbiomech.2010.11.013

Hastie, T., Tibshirani, R., & Friedman, J. (2009). *The Elements of Statistical Learning* (2 ed.). New York, USA: Springer.

Heebner, N. R., Rafferty, D. M., Wohleber, M. F., Simonson, A. J., Lovalekar, M., Reinert, A., & Sell, T. C. (2017). Landing Kinematics and Kinetics at the Knee During Different Landing Tasks. *J Athl Train, 52*(12), 1101-1108. doi:10.4085/1062-6050-52.11.25

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010. *N Am J Sports Phys Ther, 5*(4), 234-251.

Hewett, T. E., Ford, K. R., Myer, G. D., Wanstrath, K., & Scheper, M. (2006). Gender differences in hip adduction motion and torque during a single-leg agility maneuver. *J Orthop Res, 24*(3), 416-421. doi:10.1002/jor.20056

Hewett, T. E., Lynch, T. R., Myer, G. D., Ford, K. R., Gwin, R. C., & Heidt, R. S., Jr. (2010). Multiple risk factors related to familial predisposition to anterior cruciate ligament injury: fraternal twin sisters with anterior cruciate ligament ruptures. *Br J Sports Med, 44*(12), 848-855. doi:10.1136/bjsm.2008.055798

Hewett, T. E., & Myer, G. D. (2016). Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors - A Letter to the Editor. *Clinical Biomechanics*. doi:10.1016/j.clinbiomech.2016.07.007

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Jr., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med, 33*(4), 492-501. doi:10.1177/0363546504269591

Hewett, T. E., Myer, G. D., Ford, K. R., & Slauterbeck, J. R. (2007). Dynamic neuromuscular analysis training for preventing anterior cruciate ligament injury in female athletes. *Instr Course Lect, 56*, 397-406.

Hewett, T. E., Myer, G. D., Kiefer, A. W., & Ford, K. R. (2015). Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. *Med Sci Sports Exerc, 47*(12), 2579-2585. doi:10.1249/MSS.0000000000000700

Hewett, T. E., Myer, G. D., Roewer, B. D., & Ford, K. R. (2012). Letter to the editor regarding "Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention." *J Biomech, 45*(11), 2058–2060. http://doi.org/10.1016/j.jbiomech.2012.02.028

Higgins, J., & Green, S. (2009). *Cochrane Handbook for Systematic Reviews of Interventions* In. Retrieved from http://handbook.cochrane.org/

Holden, S., Colin, B., Wang, D., Doherty, C., & Delahunt, E. (2014). Two dimensional analysis of landing kinematics in male and female early adolescent secondary school athletes. *British Journal of Sports Medicine, 48*(7), 608.

Holsgaard-Larsen, A., Jensen, C., Mortensen, N. H., & Aagaard, P. (2014). Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL-patients--a cross-sectional study. *Knee, 21*(1), 66-73. doi:10.1016/j.knee.2013.06.002

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train, 42*(2), 311-319.

Houck, J. R., Duncan, A., & De Haven, K. E. (2005a). Knee and hip angle and moment adaptations during cutting tasks in subjects with anterior cruciate ligament deficiency classified as noncopers. *J Orthop Sports Phys Ther, 35*(8), 531-540. doi:10.2519/jospt.2005.35.8.531

Houck, J. R., Duncan, A., & De Haven, K. E. (2005b). Knee and hip angle and moment adaptations during cutting tasks in subjects with anterior cruciate ligament deficiency classified as noncopers. *Journal of Orthopaedic & Sports Physical Therapy, 35*(8), 531-540.

Houck, J. R., Duncan, A., & De Haven, K. E. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait Posture, 24*(3), 314-322. doi:10.1016/j.gaitpost.2005.10.005

Hughes, G. (2014). A review of recent perspectives on biomechanical risk factors associated with anterior cruciate ligament injury. *Res Sports Med, 22*(2), 193-212. doi:10.1080/15438627.2014.881821

Hughes, G., Watkins, J., & Owen, N. (2008). Gender differences in lower limb frontal plane kinematics during landing. *Sports Biomech, 7*(3), 333-341. doi:10.1080/14763140802233215

Iguchi, J., Tateuchi, H., Taniguchi, M., & Ichihashi, N. (2014). The effect of sex and fatigue on lower limb kinematics, kinetics, and muscle activity during unanticipated side-step cutting. *Knee Surg Sports Traumatol Arthrosc, 22*(1), 41-48. doi:10.1007/s00167-013-2526-8

Ireland, M. L. (2002). The female ACL: why is it more prone to injury? *Orthop Clin North Am, 33*(4), 637-651.

Jacobs, C. A., Uhl, T. L., Mattacola, C. G., Shapiro, R., & Rayens, W. S. (2007). Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train, 42*(1), 76-83.

Jamison, S. T., McNally, M. P., Schmitt, L. C., & Chaudhari, A. M. (2013). The effects of core muscle activation on dynamic trunk position and knee abduction moments: implications for ACL injury. *J Biomech, 46*(13), 2236-2241. doi:10.1016/j.jbiomech.2013.06.021

Jones, P. A., Herrington, L. C., Munro, A. G., & Graham-Smith, P. (2014). Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? *Am J Sports Med, 42*(9), 2095-2102. doi:10.1177/0363546514539446

Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. *J Athl Train, 48*(6), 810-817. doi:10.4085/1062-6050-48.6.03

Joseph, M. F., Rahl, M., Sheehan, J., MacDougall, B., Horn, E., Denegar, C. R., . . . Kraemer, W. J. (2011). Timing of lower extremity frontal plane motion differs between female and male athletes during a landing task. *Am J Sports Med, 39*(7), 1517-1521. doi:10.1177/0363546510397175

Kernozek, T., Torry, M., Shelburne, K., Durall, C. J., & Willson, J. (2013). From the gait laboratory to the rehabilitation clinic: translation of motion analysis and modeling data to interventions that impact anterior cruciate ligament loads in gait and drop landing. *Crit Rev Biomed Eng, 41*(3), 243-258.

Kernozek, T. W., Torry, M. R., H, V. A. N. H., Cowley, H., & Tanner, S. (2005). Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc, 37*(6), 1003-1012; discussion 1013.

Kester, B. S., Behery, O. A., Minhas, S. V., & Hsu, W. K. (2017). Athletic performance and career longevity following anterior cruciate ligament reconstruction in the National Basketball Association. *Knee Surg Sports Traumatol Arthrosc, 25*(10), 3031-3037. doi:10.1007/s00167-016-4060-y

Kiapour, A. M., Quatman, C. E., Goel, V. K., Wordeman, S. C., Hewett, T. E., & Demetropoulos, C. K. (2014). Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: implications for ACL injury mechanism. *Clin Biomech (Bristol, Avon), 29*(1), 75-82. doi:10.1016/j.clinbiomech.2013.10.017

Kim, J. H., Lee, K. K., Kong, S. J., An, K. O., Jeong, J. H., & Lee, Y. S. (2014). Effect of Anticipation on Lower Extremity Biomechanics During Side- and Cross-Cutting Maneuvers in Young Soccer Players. *Am J Sports Med, 42*(8), 1985-1992. doi:10.1177/0363546514531578

Kim, S. Y., Spritzer, C. E., Utturkar, G. M., Toth, A. P., Garrett, W. E., & DeFrate, L. E. (2015). Knee Kinematics During Noncontact Anterior Cruciate Ligament Injury as Determined From Bone Bruise Location. *Am J Sports Med, 43*(10), 2515-2521. doi:10.1177/0363546515594446

Kimura, Y., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Maeda, S., Hayashi, Y., & Sasaki, S. (2011). Longitudinal study of dynamic lower limb alignment during landing in pubescent children. *British Journal of Sports Medicine, 45*(4), 356-356.

Klugl, M., Shrier, I., McBain, K., Shultz, R., Meeuwisse, W. H., Garza, D., & Matheson, G. O. (2010). The prevention of sport injury: an analysis of 12,000 published manuscripts. *Clin J Sport Med, 20*(6), 407-412. doi:10.1097/JSM.0b013e3181f4a99c

Koga, H., Bahr, R., Myklebust, G., Engebretsen, L., Grund, T., & Krosshaug, T. (2011). Estimating anterior tibial translation from model-based image-matching of a noncontact anterior cruciate ligament injury in professional football: a case report. *Clin J Sport Med, 21*(3), 271-274. doi:10.1097/JSM.0b013e31821899ec

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., . . . Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med, 38*(11), 2218-2225. doi:10.1177/0363546510373570

Komdeur, P., Pollo, F. E., & Jackson, R. W. (2002). Dynamic knee motion in anterior cruciate impairment: a report and case study. *Proc (Bayl Univ Med Cent), 15*(3), 257-259.

Kristianslund, E. (2014). *Jump screening in elite handball and football players*. Paper presented at the IOC World Conference Prevention of Injury & Illness 2014, Grimaldi Forum, Monaco.

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting: implications for anterior cruciate ligament injury risk screening. *Am J Sports Med, 41*(3), 684-688. doi:10.1177/0363546512472043

Kristianslund, E., Krosshaug, T., Mok, K. M., McLean, S., & van den Bogert, A. J. (2014). Expressing the joint moments of drop jumps and sidestep cutting in different reference

frames--does it matter? *J Biomech, 47*(1), 193-199. doi:10.1016/j.jbiomech.2013.09.016
Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech, 45*(4), 666-671. doi:10.1016/j.jbiomech.2011.12.011
Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., . . . Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med, 35*(3), 359-367. doi:10.1177/0363546506293899
Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K. M., Myklebust, G., . . . Bahr, R. (2016). The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes. *Am J Sports Med, 44*(4), 874-883. doi:10.1177/0363546515625048
Kweon, C., Lederman, E. S., & Chhabra, A. (2013). Anatomy and Biomechanics of the Cruciate Ligaments and Their Surgical Implications. In G. C. Fanelli (Ed.), *The Multiple Ligament Injured Knee* (pp. 17-27). New York, NY: Springer New York.
Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007a). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *Am J Sports Med, 35*(11), 1901-1911. doi:10.1177/0363546507307400
Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007b). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *Am J Sports Med, 35*(11), 1888-1900. doi:10.1177/0363546507300823
Lee, S. P., Chow, J. W., & Tillman, M. D. (2014a). Persons with Reconstructed ACL Exhibit Altered Knee Mechanics during High-Speed Maneuvers. *Int J Sports Med*. doi:10.1055/s-0033-1358466
Lee, S. P., Chow, J. W., & Tillman, M. D. (2014b). Persons with reconstructed ACL exhibit altered knee mechanics during high-speed maneuvers. *Int J Sports Med, 35*(6), 528-533. doi:10.1055/s-0033-1358466
Lephart, S. M., Abt, J. P., Ferris, C. M., Sell, T. C., Nagai, T., Myers, J. B., & Irrgang, J. J. (2005). Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med, 39*(12), 932-938. doi:10.1136/bjsm.2005.019083
Lephart, S. M., Ferris, C. M., & Fu, F. H. (2002). Risk factors associated with noncontact anterior cruciate ligament injuries in female athletes. *Instr Course Lect, 51*, 307-310.
Leppanen, M., Pasanen, K., Krosshaug, T., Kannus, P., Vasankari, T., Kujala, U. M., . . . Parkkari, J. (2017). Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study. *Orthop J Sports Med, 5*(12), 2325967117745487. doi:10.1177/2325967117745487
Leppanen, M., Pasanen, K., Kujala, U. M., Vasankari, T., Kannus, P., Ayramo, S., . . . Parkkari, J. (2017). Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *Am J Sports Med, 45*(2), 386-393. doi:10.1177/0363546516665810
Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., . . . Moher, D. (2009). *The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration* (Vol. 339).
Liederbach, M., Dilgen, F. E., & Rose, D. J. (2008). Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a 5-year prospective study. *Am J Sports Med, 36*(9), 1779-1788. doi:10.1177/0363546508323644

Lloyd, D. G. (2001). Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. *J Orthop Sports Phys Ther, 31*(11), 645-654; discussion 661. doi:10.2519/jospt.2001.31.11.645

Lohmander, L. S., Ostenberg, A., Englund, M., & Roos, H. (2004). High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum, 50*(10), 3145-3152. doi:10.1002/art.20589

Louboutin, H., Debarge, R., Richou, J., Selmi, T. A., Donell, S. T., Neyret, P., & Dubrana, F. (2009). Osteoarthritis in patients with anterior cruciate ligament rupture: a review of risk factors. *Knee, 16*(4), 239-244. doi:10.1016/j.knee.2008.11.004

Malfait, B., Sankey, S., Firhad Raja Azidin, R. M., Deschamps, K., Vanrenterghem, J., Robinson, M. A., . . . Verschueren, S. (2014). How reliable are lower-limb kinematics and kinetics during a drop vertical jump? *Med Sci Sports Exerc, 46*(4), 678-685. doi:10.1249/MSS.0000000000000170

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon), 16*(5), 438-445.

Mall, N. A., Chalmers, P. N., Moric, M., Tanaka, M. J., Cole, B. J., Bach, B. R., Jr., & Paletta, G. A., Jr. (2014). Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med, 42*(10), 2363-2370. doi:10.1177/0363546514542796

Markatos, K., Kaseta, M. K., Lallos, S. N., Korres, D. S., & Efstathopoulos, N. (2013). The anatomy of the ACL and its importance in ACL reconstruction. *Eur J Orthop Surg Traumatol, 23*(7), 747-752. doi:10.1007/s00590-012-1079-8

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res, 13*(6), 930-935. doi:10.1002/jor.1100130618

Markolf, K. L., Graff-Radford, A., & Amstutz, H. C. (1978). In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am, 60*(5), 664-674.

Markolf, K. L., Mensch, J. S., & Amstutz, H. C. (1976). Stiffness and laxity of the knee--the contributions of the supporting structures. A quantitative in vitro study. *J Bone Joint Surg Am, 58*(5), 583-594.

Mather, R. C., 3rd, Koenig, L., Kocher, M. S., Dall, T. M., Gallo, P., Scott, D. J., . . . Group, M. K. (2013). Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am, 95*(19), 1751-1759. doi:10.2106/JBJS.L.01705

McLean, S. G. (2008). The ACL injury enigma: we can't prevent what we don't understand. *J Athl Train, 43*(5), 538-540. doi:10.4085/1062-6050-43.5.538

McLean, S. G., Huang, X., Su, A., & Van Den Bogert, A. J. (2004). Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech (Bristol, Avon), 19*(8), 828-838. doi:10.1016/j.clinbiomech.2004.06.006

McLean, S. G., Lipfert, S. W., & van den Bogert, A. J. (2004). Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc, 36*(6), 1008-1016.

McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, A. J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med, 39*(6), 355-362. doi:10.1136/bjsm.2005.018598

McLean, S. G., Walker, K. B., & van den Bogert, A. J. (2005). Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements. *J Sci Med Sport, 8*(4), 411-422. doi:https://doi.org/10.1016/S1440-2440(05)80056-8

McManus, A., Stevenson, M., Finch, C. F., Elliott, B., Hamer, P., Lower, A., & Bulsara, M. (2004). Incidence and risk factors for injury in non-elite Australian Football. *J Sci Med Sport, 7*(3), 384-391.

Meinerz, C. M., Malloy, P., Geiser, C. F., & Kipp, K. (2015). Anticipatory Effects on Lower Extremity Neuromechanics During a Cutting Task. *J Athl Train, 50*(9), 905-913. doi:10.4085/1062-6050-50.8.02

Mendiguchia, J., Ford, K. R., Quatman, C. E., Alentorn-Geli, E., & Hewett, T. E. (2011). Sex differences in proximal control of the knee joint. *Sports Med, 41*(7), 541-557. doi:10.2165/11589140-000000000-00000

Messina, D. F., Farney, W. C., & DeLee, J. C. (1999). The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. *Am J Sports Med, 27*(3), 294-299. doi:10.1177/03635465990270030401

Miranda, D. L., Fadale, P. D., Hulstyn, M. J., Shalvoy, R. M., Machan, J. T., & Fleming, B. C. (2013a). Knee biomechanics during a jump-cut maneuver: Effects of sex and ACL surgery. *Medicine and Science in Sports and Exercise, 45*(5), 942-951.

Miranda, D. L., Fadale, P. D., Hulstyn, M. J., Shalvoy, R. M., Machan, J. T., & Fleming, B. C. (2013b). Knee biomechanics during a jump-cut maneuver: effects of sex and ACL surgery. *Med Sci Sports Exerc, 45*(5), 942-951. doi:10.1249/MSS.0b013e31827bf0e4

Mohammadi, F., Salavati, M., Akhbari, B., Mazaheri, M., Khorrami, M., & Negahban, H. (2012). Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls. *Knee Surgery, Sports Traumatology, Arthroscopy, 20*(8), 1603-1610.

Mohammadi, F., Salavati, M., Akhbari, B., Mazaheri, M., Khorrami, M., & Negahban, H. (2012). Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls. *Knee Surg Sports Traumatol Arthrosc, 20*(8), 1603-1610. doi:10.1007/s00167-011-1806-4

Mok, K. M., Bahr, R., & Krosshaug, T. (2017). Reliability of lower limb biomechanics in two sport-specific sidestep cutting tasks. *Sports Biomech*, 1-11. doi:10.1080/14763141.2016.1260766

Mok, K. M., & Leow, R. S. (2016). Measurement of movement patterns to enhance ACL injury prevention - A dead end? *Asia Pac J Sports Med Arthrosc Rehabil Technol, 5*, 13-16. doi:10.1016/j.asmart.2016.06.003

Moller, M., Attermann, J., Myklebust, G., & Wedderkopp, N. (2012). Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *Br J Sports Med, 46*(7), 531-537. doi:10.1136/bjsports-2012-091022

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2016). The Effectiveness of Injury Prevention Programs to Modify Risk Factors for Non-Contact Anterior Cruciate Ligament and Hamstring Injuries in Uninjured Team Sports Athletes: A Systematic Review. *PLoS One, 11*(5), e0155272. doi:10.1371/journal.pone.0155272

Moore, M. M., Mulloy, F. E., Bridle, C., & Mullineaux, D. R. (2016, 18-22 July 2016). *Leg dominance effects on knee kinematics in unilateral and bilateral squats.* Paper presented at the 34th International Conference on Biomechanics in Sport, Tsukuba, Japan.

Morgan, K. D., Donnelly, C. J., & Reinbolt, J. A. (2014). Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: implications for anterior cruciate ligament injury risk. *J Biomech, 47*(13), 3295-3302. doi:10.1016/j.jbiomech.2014.08.016

Munro, A., Herrington, L., & Comfort, P. (2017). The Relationship Between 2-Dimensional Knee-Valgus Angles During Single-Leg Squat, Single-Leg-Land, and Drop-Jump Screening Tests. *J Sport Rehabil, 26*(1), 72-77. doi:10.1123/jsr.2015-0102

Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground reaction forces in running: a reexamination. *J Biomech, 20*(2), 147-155.

Myer, G. D., Ford, K. R., Di Stasi, S. L., Foss, K. D., Micheli, L. J., & Hewett, T. E. (2015). High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? *Br J Sports Med, 49*(2), 118-122. doi:10.1136/bjsports-2013-092536

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2010). Clinical correlates to laboratory measures for use in non-contact anterior cruciate ligament injury risk prediction algorithm. *Clin Biomech (Bristol, Avon), 25*(7), 693-699. doi:10.1016/j.clinbiomech.2010.04.016

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2011). Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med, 45*(4), 245-252. doi:10.1136/bjsm.2009.069351

Myer, G. D., Ford, K. R., Palumbo, J. P., & Hewett, T. E. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res, 19*(1), 51-60. doi:10.1519/13643.1

Myer, G. D., Ford, K. R., Paterno, M. V., Nick, T. G., & Hewett, T. E. (2008). The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med, 36*(6), 1073-1080. doi:10.1177/0363546507313572

Myer, G. D., Khoury, J., Succop, P., & Hewett, T. E. (2013). Clinic-based algorithm to identify female athletes at risk for anterior cruciate ligament injury: letter to the editor. *Am J Sports Med, 41*(1), NP1-3. doi:10.1177/0363546512470425

Myklebust, G., Engebretsen, L., Braekken, I. H., Skjolberg, A., Olsen, O. E., & Bahr, R. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med, 13*(2), 71-78.

Negrete, R. J., Schick, E. A., & Cooper, J. P. (2007). Lower-limb dominance as a possible etiologic factor in noncontact anterior cruciate ligament tears. *J Strength Cond Res, 21*(1), 270-273. doi:10.1519/R-19755.1

Nessler, T., Denney, L., & Sampley, J. (2017). ACL Injury Prevention: What Does Research Tell Us? *Curr Rev Musculoskelet Med, 10*(3), 281-288. doi:10.1007/s12178-017-9416-5

Neuman, P., Englund, M., Kostogiannis, I., Friden, T., Roos, H., & Dahlberg, L. E. (2008). Prevalence of tibiofemoral osteoarthritis 15 years after nonoperative treatment of anterior cruciate ligament injury: a prospective cohort study. *Am J Sports Med, 36*(9), 1717-1725. doi:10.1177/0363546508316770

Nguyen, A. D., & Shultz, S. J. (2007). Sex differences in clinical measures of lower extremity alignment. *J Orthop Sports Phys Ther, 37*(7), 389-398. doi:10.2519/jospt.2007.2487

Nielsen, A. B., & Yde, J. (1989). Epidemiology and traumatology of injuries in soccer. *Am J Sports Med, 17*(6), 803-807. doi:10.1177/036354658901700614

Nigg, B. M., Baltich, J., Hoerzer, S., & Enders, H. (2015). Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter'. *British Journal of Sports Medicine, 49*(20), 1290.

Nilstad, A., Bahr, R., & Andersen, T. E. (2014). Text messaging as a new method for injury registration in sports: a methodological study in elite female football. *Scand J Med Sci Sports, 24*(1), 243-249. doi:10.1111/j.1600-0838.2012.01471.x

Noyes, F. R., & Grood, E. S. (1976). The strength of the anterior cruciate ligament in humans and Rhesus monkeys. *J Bone Joint Surg Am, 58*(8), 1074-1082.

Oberlander, K. D., Bruggemann, G. P., Hoher, J., & Karamanidis, K. (2012). Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech, 45*(8), 1387-1392. doi:10.1016/j.jbiomech.2012.02.029

Oberländer, K. D., Brüggemann, G. P., Höher, J., & Karamanidis, K. (2012). Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech, 45*(8), 1387-1392.

Offord, D. R., & Kraemer, H. C. (2000). Risk factors and prevention. *Evidence Based Mental Health, 3*(3), 70.

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med, 32*(4), 1002-1012. doi:10.1177/0363546503261724

Ortiz, A., Olson, S., Libby, C. L., Trudelle-Jackson, E., Kwon, Y. H., Etnyre, B., & Bartlett, W. (2008). Landing mechanics between noninjured women and women with anterior cruciate ligament reconstruction during 2 jump tasks. *Am J Sports Med, 36*(1), 149-157. doi:10.1177/0363546507307758

Ortiz, A., Olson, S., Trudelle-Jackson, E., Rosario, M., & Venegas, H. L. (2011). Landing mechanics during side hopping and crossover hopping maneuvers in noninjured women and women with anterior cruciate ligament reconstruction. *PM R, 3*(1), 13-20. doi:10.1016/j.pmrj.2010.10.018

Padua, D. A. (2010). Executing a collaborative prospective risk-factor study: findings, successes, and challenges. *J Athl Train, 45*(5), 519-521. doi:10.4085/1062-6050-45.5.519

Padua, D. A. (2014). *The Jump ACL Study - Drop jump task can predict ACL injuries in US military cadets*. Paper presented at the IOC World Conference Prevention of Injury & Illness in Sport, Grimaldi Forum, Monaco.

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury-Prevention Program in Elite-Youth Soccer Athletes. *J Athl Train, 50*(6), 589-595. doi:10.4085/1062-6050-50.1.10

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., Jr., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med, 37*(10), 1996-2002. doi:10.1177/0363546509343200

Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med, 17*(4), 263-268. doi:10.1097/JSM.0b013e31811f415b

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech, 43*(10), 1976-1982. doi:10.1016/j.jbiomech.2010.03.008

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2016). Region-of-interest analyses of one-dimensional biomechanical trajectories: bridging 0D and 1D theory, augmenting statistical power. *PeerJ, 4*, e2652. doi:10.7717/peerj.2652

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., & Hewett, T. E. (2011). Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther, 41*(8), 553-559. doi:10.2519/jospt.2011.3591

Pfeiffer, R. P., Shea, K. G., Roberts, D., Grandstrand, S., & Bond, L. (2006). Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *J Bone Joint Surg Am, 88*(8), 1769-1774. doi:10.2106/JBJS.E.00616

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2007). Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clin J Sport Med, 17*(1), 38-42. doi:10.1097/JSM.0b013e3180305de8

Prince, J. S., Laor, T., & Bean, J. A. (2005). MRI of anterior cruciate ligament injuries and associated findings in the pediatric knee: changes with skeletal maturation. *AJR Am J Roentgenol, 185*(3), 756-762. doi:10.2214/ajr.185.3.01850756

Prodromos, C. C., Han, Y., Rogowski, J., Joyce, B., & Shi, K. (2007). A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy, 23*(12), 1320-1325 e1326. doi:10.1016/j.arthro.2007.07.003

Quatman, C. E., & Hewett, T. E. (2009). The anterior cruciate ligament injury controversy: is “valgus collapse” a sex-specific mechanism? *British Journal of Sports Medicine, 43*(5), 328-335. doi:10.1136/bjsm.2009.059139

Quatman, C. E., Quatman-Yates, C. C., & Hewett, T. E. (2010). A 'plane' explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Med, 40*(9), 729-746. doi:10.2165/11534950-000000000-00000

Quatman, C. E., Quatman, C. C., & Hewett, T. E. (2009). Prediction and prevention of musculoskeletal injury: a paradigm shift in methodology. *Br J Sports Med, 43*(14), 1100-1107. doi:10.1136/bjsm.2009.065482

Rawashdeh, S. A., Rafeldt, D. A., & Uhl, T. L. (2016). Wearable IMU for Shoulder Injury Prevention in Overhead Sports. *Sensors (Basel), 16*(11), 1847. doi:10.3390/s16111847

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., . . . Engebretsen, L. (2008). Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *Br J Sports Med, 42*(6), 394-412. doi:10.1136/bjsm.2008.048934

Robinson, M. A., Donnelly, C. J., Tsao, J., & Vanrenterghem, J. (2014). Impact of knee modeling approach on indicators and classification of anterior cruciate ligament injury risk. *Med Sci Sports Exerc, 46*(7), 1269-1276. doi:10.1249/MSS.0000000000000236

Robinson, M. A., Donnelly, C. J., Vanrenterghem, J., & Pataky, T. (2015). *Sagittal plane kinematics predict non-sagittal joint moments in*. Paper presented at the XXV Congress of the International Society of Biomechanics, Glasgow, UK.

Robinson, M. A., Sharir, R., Vanrenterghem, J., & Donnelly, C. J. (2017). *Initial explorations using the knee moment vector versus the knee abduction moment to identify athletes at risk of ACL injury*. Paper presented at the 35th Conference of the International Society of Biomechanics in Sports, Colonge, Germany.

Robinson, M. A., & Vanrenterghem, J. (2012). An evaluation of anatomical and functional knee axis definition in the context of side-cutting. *J Biomech, 45*(11), 1941-1946. doi:10.1016/j.jbiomech.2012.05.017

Roos, P. E., Button, K., Sparkes, V., & van Deursen, R. W. (2014). Altered biomechanical strategies and medio-lateral control of the knee represent incomplete recovery of individuals with injury during single leg hop. *J Biomech, 47*(3), 675-680. doi:10.1016/j.jbiomech.2013.11.046

Roos, P. E., Button, K., Sparkes, V., & van Deursen, R. W. M. (2014). Altered biomechanical strategies and medio-lateral control of the knee represent incomplete recovery of individuals with injury during single leg hop. *J Biomech, 47*(3), 675-680. doi:10.1016/j.jbiomech.2013.11.046

Ryynanen, J., Dvorak, J., Peterson, L., Kautiainen, H., Karlsson, J., Junge, A., & Borjesson, M. (2013). Increased risk of injury following red and yellow cards, injuries and goals in FIFA World Cups. *Br J Sports Med, 47*(15), 970-973. doi:10.1136/bjsports-2013-092487

Samuelsson, K., Desai, N., McNair, E., van Eck, C. F., Petzold, M., Fu, F. H., . . . Karlsson, J. (2013). Level of evidence in anterior cruciate ligament reconstruction research: a systematic review. *Am J Sports Med, 41*(4), 924-934. doi:10.1177/0363546512460647

Sankey, S. P., Raja Azidin, R. M. F., Robinson, M. A., Malfait, B., Deschamps, K., Verschueren, S., . . . Vanrenterghem, J. (2015). How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait Posture, 41*(4), 905-911. doi:https://doi.org/10.1016/j.gaitpost.2015.03.014

Sanna, G., & O'Connor, K. M. (2008). Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clin Biomech (Bristol, Avon), 23*(7), 946-954. doi:10.1016/j.clinbiomech.2008.03.065

Schwartz, M. H. & Rozumalski A. (2004). A new method for estimating joint parameters from motion data. *J Biomech, 38*(1), 107 - 116

Sell, T. C., Ferris, C. M., Abt, J. P., Tsai, Y. S., Myers, J. B., Fu, F. H., & Lephart, S. M. (2007). Predictors of proximal tibia anterior shear force during a vertical stop-jump. *J Orthop Res, 25*(12), 1589-1597. doi:10.1002/jor.20459

Shaw, L., & Finch, C. F. (2017). Trends in Pediatric and Adolescent Anterior Cruciate Ligament Injuries in Victoria, Australia 2005-2015. *Int J Environ Res Public Health, 14*(6), 599. doi:10.3390/ijerph14060599

Sheehan, F. T., Sipprell, W. H., 3rd, & Boden, B. P. (2012). Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *Am J Sports Med, 40*(5), 1068-1074. doi:10.1177/0363546512437850

Sheehan, F. T., Sipprell, W. H., & Boden, B. P. (2012). Dynamic Sagittal Plane Trunk Control During Anterior Cruciate Ligament Injury. *American Journal of Sports Medicine, 40*(5), 1068-1074.

Shimokochi, Y., & Shultz, S. J. (2008). Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train, 43*(4), 396-408. doi:10.4085/1062-6050-43.4.396

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Med Sci Sports Exerc, 43*(8), 1484-1491. doi:10.1249/MSS.0b013e31820f8395

Shultz, S. J., Schmitz, R. J., Benjaminse, A., Chaudhari, A. M., Collins, M., & Padua, D. A. (2012). ACL Research Retreat VI: an update on ACL injury risk and prevention. *J Athl Train, 47*(5), 591-603. doi:10.4085/1062-6050-47.5.13

Smith, H. C., Johnson, R. J., Shultz, S. J., Tourville, T., Holterman, L. A., Slauterbeck, J., . . . Beynnon, B. D. (2012). A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. *Am J Sports Med, 40*(3), 521-526. doi:10.1177/0363546511429776

Soderman, K., Alfredson, H., Pietila, T., & Werner, S. (2001). Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc, 9*(5), 313-321. doi:10.1007/s001670100228

Stearns, K. M., & Pollard, C. D. (2013). Abnormal Frontal Plane Knee Mechanics During Sidestep Cutting in Female Soccer Athletes After Anterior Cruciate Ligament Reconstruction and Return to Sport. *American Journal of Sports Medicine, 41*(4), 918-923.

Stearns, K. M., & Pollard, C. D. (2013). Abnormal frontal plane knee mechanics during sidestep cutting in female soccer athletes after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med, 41*(4), 918-923. doi:10.1177/0363546513476853

Steffen, K., Myklebust, G., Olsen, O. E., Holme, I., & Bahr, R. (2008). Preventing injuries in female youth football--a cluster-randomized controlled trial. *Scand J Med Sci Sports, 18*(5), 605-614. doi:10.1111/j.1600-0838.2007.00703.x

Sutton, K. M., & Bullock, J. M. (2013). Anterior cruciate ligament rupture: differences between males and females. *J Am Acad Orthop Surg, 21*(1), 41-50. doi:10.5435/JAAOS-21-01-41

Swanik, C. B., Covassin, T., Stearne, D. J., & Schatz, P. (2007). The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med, 35*(6), 943-948. doi:10.1177/0363546507299532

Swart, E., Redler, L., Fabricant, P. D., Mandelbaum, B. R., Ahmad, C. S., & Wang, Y. C. (2014). Prevention and screening programs for anterior cruciate ligament injuries in young athletes: a cost-effectiveness analysis. *J Bone Joint Surg Am, 96*(9), 705-711. doi:10.2106/JBJS.M.00560

Taylor, J. B., Ford, K. R., Nguyen, A. D., & Shultz, S. J. (2016). Biomechanical Comparison of Single- and Double-Leg Jump Landings in the Sagittal and Frontal Plane. *Orthop J Sports Med, 4*(6), 2325967116655158. doi:10.1177/2325967116655158

Taylor, J. B., Waxman, J. P., Richter, S. J., & Shultz, S. J. (2015). Evaluation of the effectiveness of anterior cruciate ligament injury prevention programme training components: a systematic review and meta-analysis. *Br J Sports Med, 49*(2), 79-87. doi:10.1136/bjsports-2013-092358

Thomas, A. C., McLean, S. G., & Palmieri-Smith, R. M. (2010). Quadriceps and hamstrings fatigue alters hip and knee mechanics. *J Appl Biomech, 26*(2), 159-170.

Ting, L. H., Chiel, H. J., Trumbower, R. D., Allen, J. L., McKay, J. L., Hackney, M. E., & Kesar, T. M. (2015). Neuromechanical principles underlying movement modularity and their implications for rehabilitation. *Neuron, 86*(1), 38-54. doi:10.1016/j.neuron.2015.02.042

Tranaeus, U., Gotesson, E., & Werner, S. (2016). Injury Profile in Swedish Elite Floorball. *Sports Health, 8*(3), 224-229. doi:10.1177/1941738116628472

Tsai, L. C., Sigward, S. M., Pollard, C. D., Fletcher, M. J., & Powers, C. M. (2009). Effects of fatigue and recovery on knee mechanics during side-step cutting. *Med Sci Sports Exerc, 41*(10), 1952-1957. doi:10.1249/MSS.0b013e3181a4b266

UK, P. H. (2017, 15 November 2017). How much does a private Knee ligament surgery (ACL reconstruction) cost in the UK? . Retrieved from https://www.privatehealth.co.uk/conditions-and-treatments/knee-ligament-surgery-acl-reconstruction/costs/

Vairo, G. L., Myers, J. B., Sell, T. C., Fu, F. H., Harner, C. D., & Lephart, S. M. (2008a). Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*(1), 2-14.

Vairo, G. L., Myers, J. B., Sell, T. C., Fu, F. H., Harner, C. D., & Lephart, S. M. (2008b). Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc, 16*(1), 2-14. doi:10.1007/s00167-007-0427-4

van der Horst, N., Smits, D. W., Petersen, J., Goedhart, E. A., & Backx, F. J. (2015). The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *Am J Sports Med, 43*(6), 1316-1323. doi:10.1177/0363546515574057

van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med, 14*(2), 82-99.

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS One, 12*(12), e0189876. doi:10.1371/journal.pone.0189876

Vanrenterghem, J., Gormley, D., Robinson, M. A., & Lees, A. (2010). Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait Posture, 31*(4), 517-521. doi:10.1016/j.gaitpost.2010.02.014

Vanrenterghem, J., Venables, E., Pataky, T., & Robinson, M. A. (2012). The effect of running speed on knee mechanical loading in females during side cutting. *J Biomech, 45*(14), 2444-2449. doi:10.1016/j.jbiomech.2012.06.029

von Porat, A., Henriksson, M., Holmstrom, E., Thorstensson, C. A., Mattsson, L., & Roos, E. M. (2006). Knee kinematics and kinetics during gait, step and hop in males with a 16 years old ACL injury compared with matched controls. *Knee Surg Sports Traumatol Arthrosc, 14*(6), 546-554. doi:10.1007/s00167-006-0071-4

von Porat, A., Henriksson, M., Holmström, E., Thorstensson, C. A., Mattsson, L., & Roos, E. M. (2006). Knee kinematics and kinetics during gait, step and hop in males with a 16 years old ACL injury compared with matched controls. *Knee Surgery, Sports Traumatology, Arthroscopy, 14*(6), 546-554.

Walden, M., Hagglund, M., Werner, J., & Ekstrand, J. (2011). The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. *Knee Surg Sports Traumatol Arthrosc, 19*(1), 3-10. doi:10.1007/s00167-010-1172-7

Webster, K. A., & Gribble, P. A. (2010a). Time to Stabilization of Anterior Cruciate Ligament--Reconstructed Versus Healthy Knees in National Collegiate Athletic Association Division I Female Athletes. *J Athl Train, 45*(6), 580-585.

Webster, K. A., & Gribble, P. A. (2010b). Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes. *J Athl Train, 45*(6), 580-585. doi:10.4085/1062-6050-45.6.580

Webster, K. E., Gonzalez-Adrio, R., & Feller, J. A. (2004). Dynamic joint loading following hamstring and patellar tendon anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc, 12*(1), 15-21. doi:10.1007/s00167-003-0400-9

Whelan, D., O' Reilly, M., Huang, B., Giggins, O., Kechadi, T., & Caulfield, B. (2016, 16-20 Aug. 2016). *Leveraging IMU data for accurate exercise performance classification and musculoskeletal injury risk screening.* Paper presented at the 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).

Wong, P., & Hong, Y. (2005). Soccer injury in the lower extremities. *Br J Sports Med, 39*(8), 473-482. doi:10.1136/bjsm.2004.015511

Woo, S. L., Debski, R. E., Withrow, J. D., & Janaushek, M. A. (1999). Biomechanics of knee ligaments. *Am J Sports Med, 27*(4), 533-543. doi:10.1177/03635465990270042301

Woo, S. L., Hollis, J. M., Adams, D. J., Lyon, R. M., & Takai, S. (1991). Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med, 19*(3), 217-225. doi:10.1177/036354659101900303

Woodland, L. H., & Francis, R. S. (1992). Parameters and comparisons of the quadriceps angle of college-aged men and women in the supine and standing positions. *Am J Sports Med, 20*(2), 208-211. doi:10.1177/036354659202000220

Yamazaki, J., Muneta, T., Ju, Y. J., & Sekiya, I. (2009). Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surgery, Sports Traumatology, Arthroscopy, 18*(1), 56-63.

Yamazaki, J., Muneta, T., Ju, Y. J., & Sekiya, I. (2010). Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surg Sports Traumatol Arthrosc, 18*(1), 56-63. doi:10.1007/s00167-009-0892-z

Yeow, C. H., Lee, P. V., & Goh, J. C. (2010). Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *Knee, 17*(2), 127-131. doi:10.1016/j.knee.2009.07.015

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. *Br J Sports Med, 41 Suppl 1*(Suppl 1), i47-51. doi:10.1136/bjsm.2007.037192

Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Res Bull, 67*(4), 304-309. doi:10.1016/j.brainresbull.2005.06.035

Zazulak, B. T., Ponce, P. L., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther, 35*(5), 292-299. doi:10.2519/jospt.2005.35.5.292

Zebis, M. K., Andersen, L. L., Bencke, J., Kjaer, M., & Aagaard, P. (2009). Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med, 37*(10), 1967-1973. doi:10.1177/0363546509335000

Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med, 31*(3), 449-456. doi:10.1177/03635465030310032101

# Appendices

Appendix A. Selected level 3 evidence papers research trend

The supplementary data is available at https://ars.els-cdn.com/content/image/1-s2.0-S0268003316300882-mmc1.xlsx

Appendix B. Sports and Injury History Questionnaire

## SPORTS AND INJURY HISTORY QUESTIONNAIRE

Name: ______________________________ Gender: Male / Female DoB: ___/___/___

Phone: ______________________________ ID: ______________________

**Sports participation history**

| Sport | Number of years | From | Until | Level |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**Sporting participation** ***Yes*** ***No***

2. Are you currently playing sports competitively or recreationally? ☐ ☐
   If no why not (e.g. out of playing season)?
   ____________________________________________________________

3. How often per week do you participate in: ☐ ☐
   a) Training _________ mins
   b) Competitive match-play _________ mins
   c) Recreational activity _________ mins

4. In which sport/s are you currently participating and how long have you been participating? ☐ ☐

**Injury history – past 12 months**

5. Did you suffer any injury during this past 12 months?
   If yes, please state what was the injury: ______________________________

6. Did the injury occurred during a sporting / recreational activity? ☐ ☐

7. Did the injury led to the discontinuation of sport / recreational activity? ☐ ☐

**Extended Injury history**

8. Have you ever fractured or broken any bones in your body? Bone Fractured and Date: ____________________ ☐ ☐

9. Have you ever dislocated any joint in your body? Joint Dislocated and Date: ____________________ ☐ ☐

10. Have you ever had surgery done as a direct result of a fracture or dislocation? ☐ ☐

11. Do you have a pin, wire, plate, or screw in your body as a result of surgery? Where? ____________________________ ☐ ☐

12. Have you ever had an injury to your back for which you sought medical attention? ☐ ☐

13. Do you continue to experience back pain? If yes please specify ____________________________________________ ☐ ☐

14. Have you ever injured ligaments, cartilage, or any other structures in your knee or ankle? ☐ ☐

15. Does your knee or ankle hurt after vigorous physical activity? ☐ ☐

16. Have you ever had surgery to the lower limb? If YES, please specify the type and approximate date ______________________________________________________________ ☐ ☐

**Risk takers**

17. A risk taker can be defined as someone who risks loss or injury in hope of gain or excitement. Do you consider yourself as a risk taker? ☐ ☐

Appendix C. Exercise Readiness Questionnaire

# Exercise Readiness Questionnaire (ERQ)

| Name | | | Date |
|---|---|---|---|
| DOB | Age | Email | ID |

Regular exercises is associated with many health benefits. Participating in physical activity is safe for most people. However, some individuals should check with a physician before becoming physically active. Completion of this questionnaire is a first step to assess your readiness to exercise. Please answer honestly:

| | |
|---|---|
| 1) Has a physician ever diagnosed you with a heart condition **and** indicated you should restrict your physical activity? | |
| 2) When you perform physical activity, do you feel pain in your chest? | |
| 3) When you were not engaging in physical activity, have you experienced chest pain in the past month? | |
| 4) Do you ever faint or get dizzy and lose your balance? | |
| 5) Do you have an injury or orthopedic condition (such as a back, hip, or knee problem) that may worsen due to a change in your physical activity? | |
| 6) Do you have high blood pressure or a heart condition in which a physician is currently prescribing a medication? | |
| 7) Are you pregnant? | |
| 8) Do you have insulin dependent diabetes? | |
| 9) Are you 69 years of age or older **and** not used to being very active? | |
| 10) Do you know of any other reason you should not exercise or increase your physical activity? | |
| Yes | No |

If you answered yes to any of the above questions, talk with your doctor **before** participating in this study. Tell your doctor your plan to exercise and to which question/s you answered yes.

If you answered no to all questions then you certify that there is no known reason why you could not participate in this study.

Participant Signature　　　　　　　　　　　　Date

_____________________　　　　　　　　　　_______________

Appendix D. Inform consent form

**LIVERPOOL JOHN MOORES UNIVERSITY**
**CONSENT FORM**

Identification of biomechanical and neuromuscular risk factors for knee injury during dynamic activities: A Prospective Study

Prospective Two-Year Follow-Up of the Biomechanical Risk Factors for Knee Injury during Dynamic Sporting Activities

Raihana Sharir & Radin Rafeeuddin/ School of Sport and Exercise Science/ Faculty of Science

1. I confirm that I have read and understand the information provided for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and that this will not affect my legal rights

3. I understand that any personal information collected during the study will be anonymised and remain confidential

4. I agree to take part in the above study

5. I agree to provide an email address to be used by the mobile application to identify me

6. I consent to the public use of images / video of me as long as my face is blurred / masked.

| Name of Participant | Date | Signature |
|---|---|---|
| Name of Researcher | Date | Signature |
| Name of Person taking consent | Date | Signature |

*Note: Two copies are to be completed; 1 copy for the participant and 1 copy for the researcher*

Appendix E. Exposure monitoring questionnaire

LIVERPOOL JOHN MOORES UNIVERSITY

Liverpool Knee Injury Study

**EXPOSURE MONITORING QUESTIONNAIRE**

*ID: ____________________* *E-mail address: _________________*

1. *Why are you not participating in your sport as declared?*

- ☐ *Previously declared injury*
- ☐ *Lower limb injury*
- ☐ *New injury (not lower-limb)*
- ☐ *Holiday*
- ☐ *Illness*
- ☐ *Reserve/Substitution*
- ☐ *Loss of Interest*
- ☐ *Personal Issues*
- ☐ *Graduated/Migrated*
- ☐ *Time Constraint (work, study etc.)*
- ☐ *Changed sports*
- ☐ *Other ______________________*

*(Continue to questions 2, 3 & 4 ONLY if you ticked NEW INJURY)*

*2. Did you get the INJURY (not lower-limb) when participating in SPORT RELATED activity?*

☐ *Yes* ☐ *No*

*If NO please state how the injury occurred:*

__________________________________________________________________________________

_____________________________________________

*3. What was the date of the injury? _______________________*

*4. Did you seek medical attention for a diagnosis?*

*Medical diagnosis: ___________________________*

*Self diagnosis: ___________________________*

*5. How long do you anticipate it will be before you return to sports participation?*

- ☐ *1-7 days*
- ☐ *8-21 days*
- ☐ *>21 days*

Appendix F. Post-injury questionnaire (lower limb)

# Post Injury Questionnaire (Lower-limb)

Liverpool Knee Injury Study

ID : ____________________

Date of Injury : ___/___/___

Cohort Number : 1 / 2 / 3 / 4 / 5 / 6

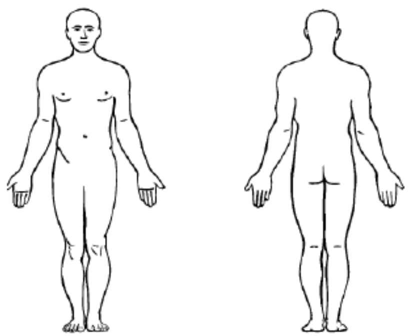
**Was the injury sports related**
- ☐ Yes ____________
- ☐ No ____________

**Type of activity at time of injury**
- ☐ Training
- ☐ Warm-up/cool down
- ☐ Competitive sport
- ☐ Other ____________

**When did the injury happen?**
- ☐ First half
- ☐ Second half
- ☐ Time (minutes)________

**Body region injured**

Tick or circle body part/s injured & name



*Please indicate right/left/front/back correctly*

**Mechanism of injury**
- ☐ Struck by other player (e.g. tacked, kicked, pushed)
- ☐ Struck by ball or object
- ☐ Collision with other individual
- ☐ Collision with fixed object
- ☐ Fall/stumble (non-contact)
- ☐ Slip/trip (non-contact)
- ☐ Jumping (non-contact)
- ☐ Landing (non-contact)
- ☐ Sprinting (non-contact)
- ☐ Turning (non-contact)
- ☐ Likely overexertion (chronic)
- ☐ Other ____________
- ☐ Don't know

Can you explain more exactly how the incident occurred (is there a video record?):

____________________

____________________

____________________

Are there any other contributing factors to the injury e.g. unsuitable footwear, playing surface, equipment, foul play?

____________________

____________________

____________________

**Protective / supportive equipment**

Was protective / supporting equipment e.g. guard, brace, tape, spray, warming agent being worn on the injured body part?
- ☐ Yes ____________
- ☐ No

**Nature of injury**
- ☐ Sprain (ligament)
- ☐ Strain (muscle)
- ☐ Fracture
- ☐ Dislocation/subluxation
- ☐ Other ____________

**Self diagnosis**

____________________

**Provisional severity assessment**
- ☐ Mild (1-7 days modified activity)
- ☐ Moderate (8-21 days modified activity)
- ☐ Severe (>21 days modified or lost)

**Medical Consultation**
- ☐ None
- ☐ General practitioner
- ☐ Physiotherapist
- ☐ Hospital (A&E)
- ☐ Others ____________

**Medical diagnosis**

____________________

**Treating person**
- ☐ Medical practitioner
- ☐ Sports physio
- ☐ None
- ☐ Other ____________

**Advice given**
- ☐ Immediate return, unrestricted activity
- ☐ Able to return with restriction
- ☐ Unable to return at the present time
- ☐ Able to return but the player chose not to
- ☐ Referred for further assessment before returning to activity

**Initial Treatment**
- ☐ None given (not required)
- ☐ RICER
- ☐ dressing
- ☐ Sling/splint
- ☐ Crutches
- ☐ Stretch/exercise
- ☐ Taping only
- ☐ None given – referred
- ☐ Other ____________

Appendix G. Knee injury questionnaire

LIVERPOOL JOHN MOORES UNIVERSITY

Liverpool Knee Injury Study

**KNEE INJURY QUESTIONNAIRE**

ID: ____________________ E-mail address: ____________________

☐ **Tick on the related injuries as diagnosed by the medical staff.**

| **Knee Sprains/ Ligament Injuries** | | |
|---|---|---|
| | Acute ACL injury | |
| | | Partial ACL tear |
| | | ACL rupture |
| | | Isolated ACL strain/ rupture with chondral/ meniscal injury |
| | | ACL graft rupture |
| | Acute PCL injury | |
| | | Partial PCL tear |
| | | PCL rupture |
| | | PCL strain/ rupture with associated chondral/ meniscal injury |
| | MCL injury knee | |
| | | Grade 1 MCL tear knee |
| | | Grade 2 MCL tear knee |
| | | MCL rupture knee |
| | | MCL strain/ rupture with chondral/ meniscal damage knee |
| | | Complication post MCL strain/ rupture incl Pellegrini Steida lesion |
| | Posterolateral corner and LCL ligament injuries knee | |
| | | LCL strain/ rupture |
| | | Posterolateral corner strain/ rupture |
| | | PLC injury with chondral / meniscal injury |
| | Patellar subluxation | |
| | Combined ligament injuries knee | |
| | | Combined ligament injury with chondral/meniscal injury |
| | Superior tib fib joint sprain | |

| Knee Cartilage Injury (Chondral/ Osteochondral/ Meniscal) | | |
|---|---|---|
| | Knee osteochondral injury | |
| | | Medial femoral condyle osteochondral injury |
| | | Lateral femoral condyle osteochondral injury |
| | | Tibial osteochondral injury |
| | | Patellofemoral osteochondral injury |
| | | Two or more osteochondral injury sites |
| | Knee cartilage injury with loose bodies | |
| | Knee Meniscal cartilage injury | |
| | | Medial meniscal tear |
| | | Lateral meniscal tear |
| | | Lateral meniscal cyst |
| | | Medial and lateral meniscal tears |
| | | Degenerative meniscal tear |
| | Mixed osteochondral and meniscal injury | |

| Knee Dislocation | | |
|---|---|---|
| | Patellar dislocation | |
| | | Patellar dislocation with avulsion fracture patella |
| | Knee dislocation | |
| | | Knee dislocation with neural or vascular complication |
| | Superior tib fib joint dislocation | |

| Knee Instability (Chronic or recurrent subluxations) | |
|---|---|
| | Patellar instability |
| | Chronic ACL insufficiency |
| | Chronic PCL insufficiency |
| | Chronic MCL insufficiency |
| | Other instability |

| Knee Impingement/ Synovitis/ Biomechanical Lesion not associated with other conditions | | |
|---|---|---|
| | **Patellofemoral pain** | |
| | | Patellofemoral pain with patellar tendinopathy |
| | | Excess lateral pressure syndrome |
| | | Hoffa's fat pad impingement |
| | | PFS related to bipartite patella |
| | ITB friction syndrome | |
| | Knee joint synovitis | |
| | | Synovial plica of knee |
| | Bakers Cyst | |
| | | Ruptured Bakers Cyst |

| Knee Fractures | | |
|---|---|---|
| | Patellar fracture | |
| | Distal femoral fracture | |
| | | Intraarticular femoral fracture |
| | Proximal tibial fracture | |
| | | Intraarticular tibial fracture |

| Knee Stress Fracture | |
|---|---|
| | Patellar stress fracture |
| | Distal femoral stress fracture |
| | Proximal tibial stress fracture |

| Knee Osteoarthritis | |
|---|---|
| | Patellofemoral osteoarthritis |
| | Medial compartment osteoarthritis knee |
| | Lateral compartment osteoarthritis knee |
| | Bi or tri-comparmental osteoarthritis |

| Knee Pain/ Injury Not otherwise specified | |
|---|---|
| | Knee pain undiagnosed |
| | Knee haemarthrosis cause undiagnosed |

Appendix H. KOOS Knee Survey

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

# KOOS KNEE SURVEY

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

Name: ________________________________________________

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

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

S1. Do you have swelling in your knee?

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S4. Can you straighten your knee fully?

| Always | Often | Sometimes | Rarely | Never |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S5. Can you bend your knee fully?

| Always | Often | Sometimes | Rarely | Never |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

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

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Pain**

P1. How often do you experience knee pain?

| Never | Monthly | Weekly | Daily | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

P2. Twisting/pivoting on your knee

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P3. Straightening knee fully

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P4. Bending knee fully

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P5. Walking on flat surface

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P6. Going up or down stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P7. At night while in bed

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P8. Sitting or lying

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P9. Standing upright

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Function, daily living**

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

A1. Descending stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A2. Ascending stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

A3. Rising from sitting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A4. Standing

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A5. Bending to floor/pick up an object

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A6. Walking on flat surface

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A7. Getting in/out of car

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A8. Going shopping

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A9. Putting on socks/stockings

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A10. Rising from bed

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A11. Taking off socks/stockings

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A13. Getting in/out of bath

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A14. Sitting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A15. Getting on/off toilet

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

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

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Function, sports and recreational activities**

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

SP1. Squatting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

SP2. Running

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

SP3. Jumping

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

SP4. Twisting/pivoting on your injured knee

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

SP5. Kneeling

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Quality of Life**

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

| Never | Monthly | Weekly | Daily | Constantly |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

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

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

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

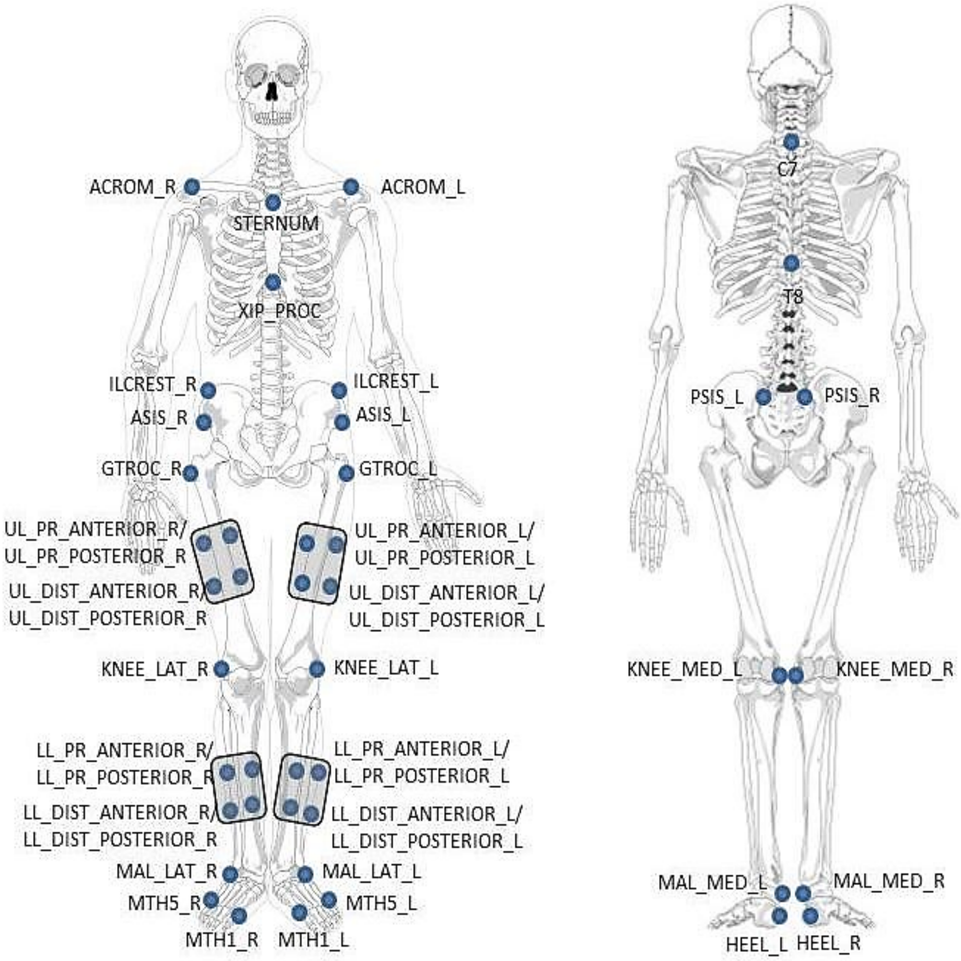
Q4. In general, how much difficulty do you have with your knee?

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

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

Appendix I. LJMU Lower-limb and trunk model

Physically placed markers




<u>Anatomical Markers</u>

| | |
|---|---|
| **Trunk** | |
| C7 | Processus spinosus vertebra C7 |
| STERNUM | Sternum |
| XIP_PROC | Xiphoid process |
| T8 | Processus spinous vertebra T8 |
| ACROM_L | Acromion left (acromioclavicular joint) |
| ACROM_R | Acromion right (acromioclavicular joint) |
| **Pelvis** | |
| ASIS_L | Anterior sacral iliac spine left |
| PSIS_L | Posterior sacral iliac spine left |
| ILCREST_L | Iliac crest left |
| ASIS_R | Anterior sacral iliac spine right |
| PSIS_R | Posterior sacral iliac spine right |
| ILCREST_R | Iliac crest right |
| **Lower limbs** | |
| GTROC_L | Greater trochanter left |
| KNEE_MED_L | Knee medial femoral epicondyle left |

| | |
|---|---|
| KNEE_LAT_L | Knee lateral femoral epicondyle left |
| MAL_MED_L | Malleolus medial left |
| MAL_LAT_L | Malleolus lateral left |
| HEEL_L | Heel left |
| MTH1_L | Metatarsal head 1 left |
| MTH5_L | Metatarsal head 5 left |
| GTROC_R | Greater trochanter right |
| KNEE_MED_R | Knee medial femoral epicondyle right |
| KNEE_LAT_R | Knee lateral femoral epicondyle right |
| MAL_MED_R | Malleolus medial right |
| MAL_LAT_R | Malleolus lateral right |
| HEEL_R | Heel right |
| MTH1_R | Metatarsal head 1 right |
| MTH5_R | Metatarsal head 5 right |

Marker Clusters

| | |
|---|---|
| UL_PR_ANT_L | Upper leg proximal anterior left |
| UL_PR_POST_L | Upper leg proximal posterior left |
| UL_DI_ANT_L | Upper leg distal anterior left |
| UL_DI_POST_L | Upper leg distal posterior left |
| LL_PR_ANT_L | Lower leg proximal anterior left |
| LL_PR_POST_L | Lower leg proximal posterior left |
| LL_DI_ANT_L | Lower leg distal anterior left |
| LL_DI_POST_L | Lower leg distal posterior left |
| UL_PR_ANT_R | Upper leg proximal anterior right |
| UL_PR_POST_R | Upper leg proximal posterior right |
| UL_DI_ANT_R | Upper leg distal anterior right |
| UL_DI_POST_R | Upper leg distal posterior right |
| LL_PR_ANT_R | Lower leg proximal anterior right |
| LL_PR_POST_R | Lower leg proximal posterior right |
| LL_DI_ANT_R | Lower leg distal anterior right |
| LL_DI_POST_R | Lower leg distal posterior right |

Virtual landmarks

| | |
|---|---|
| THORAX_PROX | Midpoint between C7 and STERNUM |
| THORAX_DIST | Midpoint between T8 and XIP_PROC |
| F_L(R)HIP | Functional hip joint |
| F_L(R)KNEE | Functional knee joint |
| F_L(R)KNEE_X | Projected landmark offset along functional knee axis |
| L(R)LK | Lateral knee joint marker projected onto functional knee axis |
| L(R)MK | Medial knee joint marker projected onto functional knee axis |
| L(R)ANKLE | Midpoint between MAL_MED_L(R) and MAL_LAT_L(R) |
| L(R)TOE | Midpoint between MTH1 and MTH5 |

Segment definitions (anatomical and technical frames)

**Thorax/Abdomen:**

**Origin**: Midpoint of the line connecting the ACROM_R and ACROM_L
**Z-axis**: Line connecting the Origin and the midpoint of ILCREST_R and ILCREST_L, pointing vertically
**Y-axis**: Line perpendicular to the Z-axis and a least-squares plane fit to the ACROM_L, ACROM_R, ASIS_L and ASIS_R, pointing anteriorly
**X-axis**: Cross-product of the plane formed by the Z and Y axes, pointing laterally
**Tracking Markers**: C7, STERNUM, T8, XIP_PROC

**Pelvis:**

**Origin**: Midpoint of the line connecting ILCREST_R and ILCREST_L
**Z-axis**: Line connecting the Origin to the midpoint of the line connecting the GTROC_R and GTROC_L, pointing vertically
**Y-axis**: Line perpendicular to the Z-axis and a least-squares plane fit to the ILCREST_R, ILCREST_L, GTROC_L and GTROC_L, pointing anteriorly
**X-axis**: Cross-product of the plane formed by the Z and Y-axes, pointing laterally **Tracking Markers**: From ASIS, PSIS, ILCREST

**Thighs:**

**Origin**: Coincident with F_L(R)HJC
**Z-axis**: Line connecting F_L(R)HJC to midpoint of the line connecting L(R)LK and L(R)MK, pointing upwards
**Y-axis**: Line perpendicular to the Z-axis and the plane formed by L(R)LK and L(R)MK, pointing anteriorly
**X-axis**: Cross-product of the plane formed by the Z- and Y-axes, pointing laterally
**Tracking Markers**: Upper Leg marker cluster

**Shanks:**

**Origin**: Midpoint of the line connecting L(R)LK and L(R)MK
**Z-axis**: Line connecting midpoint of the L(R)LK and L(R)MK and L(R)ANKLE, pointing vertically
**Y-axis**: Line perpendicular to the Z-axis and the plane formed by the L(R)MK, L(R)LK and L(R)ANKLE, pointing anteriorly
**X-axis**: Cross-product of the plane formed by the Z and Y-axes, pointing laterally
**Tracking Markers**: Lower Leg marker cluster

**Feet:**

**Origin**: Coincident with L(R)ANKLE
**Z-axis**: Line connecting L(R)ANKLE and the midpoint of the line between MTH5_L(R) and MTH1_ L(R), pointing posteriorly
**Y-axis**: Line perpendicular to the Z-axis and plane formed by the L(R)ANKLE, MTH5_L(R) and MTH1_L(R), projecting vertically
**X-axis**: Cross-product of the plane formed by the Z and Y-axes, pointing right
**Tracking Markers**: From HEEL, MTH5, MTH1, MAL_LAT

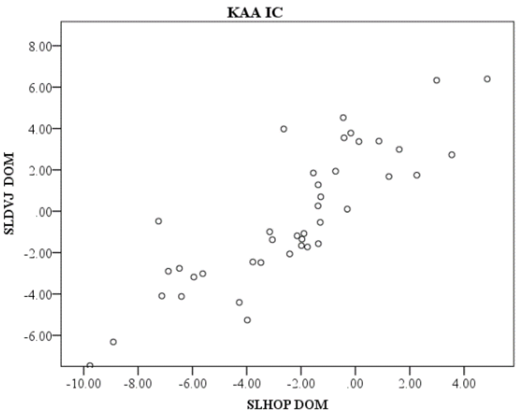
**Virtual Feet:**

**Origin**: Coincident with HEEL_L(R)

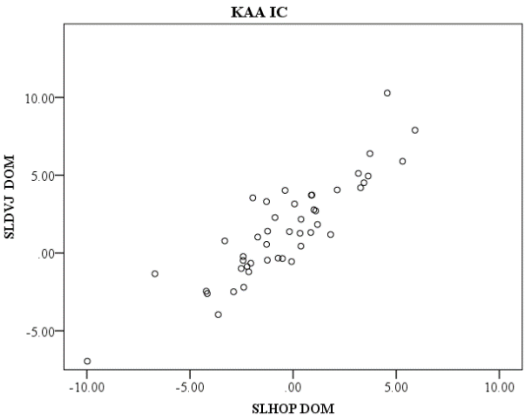
**Z-axis**: Line connecting HEEL_L(R) and L(R)TOE, pointing vertically
**Y-axis**: Line perpendicular to the Z-axis and plane formed by the HEEL_L(R), L(R)TOE & RANKLE, pointing anteriorly
**X-axis**: Cross-product of the plane formed by the Z and Y-axes, pointing laterally **Tracking Markers**: HEEL, MTH5, MTH1

Appendix J. Example scatterplots and graphs of risk factors across different task

Good

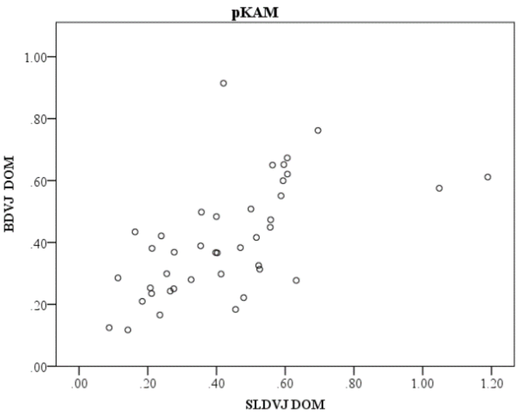



F DOM
ρ = 0.85
CV = 11.38 SLDVJ, 1.45 SLHOP

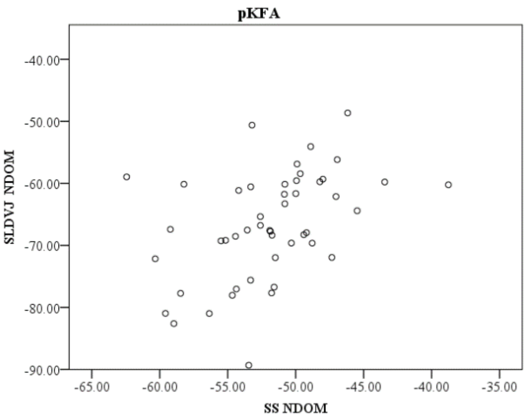



M DOM
p = 0.86
CV = 2.17 SLDVJ, 7.56 SLHOP

Moderate

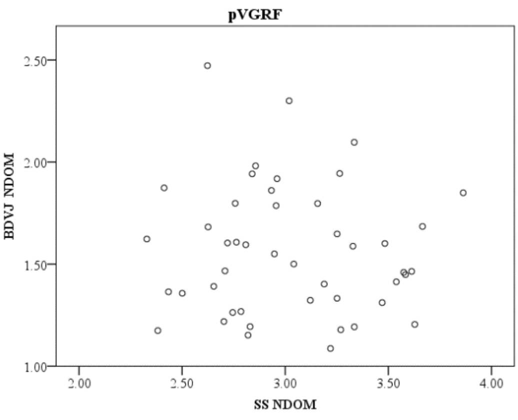



F DOM
ρ = 0.67
CV = 0.45 BDVJ, 0.53 SLDVJ

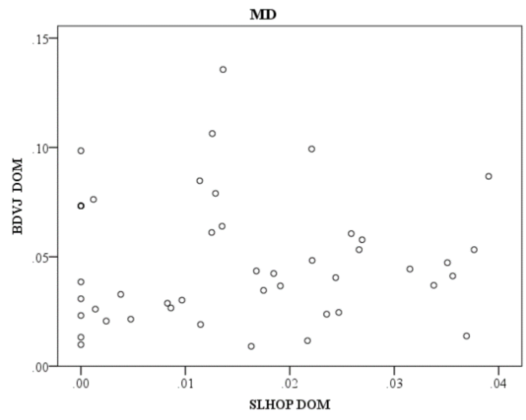



M NDOM
ρ = 0.50
CV = 0.13 SLDVJ, 0.09 SS

Poor




M NDOM
ρ = -0.02
CV = 0.20 BDVJ, 0.13 SS




M DOM
ρ = 0.06
CV = 0.60 BDVJ, 0.84 SLHOP