Effect of soccer match-play on markers of anterior cruciate ligament injury risk

By

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Abstract

Non-contact anterior cruciate ligament (ACL) injuries have a high prevalence in soccer players, and this particularly during the latter stages of match-play. Gaining a better understanding of how match-play increases ACL injury risk will benefit the development of effective screening and injury prevention programmes. This thesis therefore aimed to investigate the effects of simulating soccer match-play on markers of ACL injury risk. First, 45 min treadmill versus overground match-play simulations were evaluated for external validity by observing physiological responses and key biomechanical and muscular strength related markers of ACL injury risk. Generally, overground simulations demonstrated physiological responses that were more similar to actual soccer match-play than treadmill simulations, and for some of the markers of ACL injury risk the expected detrimental effects were greater, albeit only in males. These markers were mostly related with reduced hamstrings eccentric peak torques. With this notion that overground simulations better represent actual match-play demands, the influence of a 90 min overground simulation on muscle strength markers, and on biomechanical markers during unanticipated side cutting manoeuvres were investigated. This confirmed the previous observations, whilst also showing more extended knee extension angles at initial contact, and an unexpected reduction in peak knee abduction moments over time. Overall though, sufficient evidence was gathered that certain impairments in muscle strength and altered knee and hip mechanics, particularly in the second playing half and even immediately following a passive half time rest, may induce increased ACL injury risk. Finally, the potential to reverse these impairments was investigated through an intervention involving re-warm up during half-time. The re-warm up intervention could not reverse the impairments, yet the outcome revealed some valuable practical implications. Overall, this

work has helped gain a greater understanding for the development of better screening and injury prevention programmes.

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List of Abbreviations, Acronyms and Symbols

ACL	anterior cruciate ligament
beats · min^{-1}	beats per minutes
CON	control condition
DL	dominant limb
EMG	electromyography
FIFA	Federation Internationale de Football Association
h	hours
H_{con}	concentric hamstrings
H_{ecc}	eccentric hamstrings
H_{con}:Q_{con}	concentric hamstrings:concentric quadriceps ratio
H_{ecc}:Q_{con}	eccentric hamstrings:concentric quadriceps ratio
HR	heart rate
HR_{max}	maximal heart rate
IC	initial contact
km	kilometres
km · h^{-1}	kilometres per hour
m	meters
min	minutes
m ·s^{-2}	meter per second squared
n	number of participants in samples
N	newton
NDL	non dominant limb
N · m	newton meters
N · m kg^{-1}	newton meters per kilogram

Q_{con}	concentric quadriceps
RPE	rate of perceived exertion
RWU	re-warm up
$SAFT^{90}$	90 min soccer-specific aerobic field test
SD	standard deviation
VO_{2max}	maximal oxygen uptake
vs	versus
y	years
°	degrees
°C	degrees celcius

Chapter 1

General Introduction

1.1 Introduction

According to the most recent Big Count survey by the Federation Internationale de Football Association (FIFA) (2006), association football, commonly referred to as soccer, is the most commonly played sport in the world. It has an estimated 265 million players actively involved in soccer around the world, roughly about 4 percent of the world's population. The great interest and popularity of soccer around the globe unfortunately also leads to a substantial amount of injuries especially in the lower extremity during training and matches, in both professional and amateur level soccer players (Azubuike & Okojie, 2009; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001; Wong & Hong, 2005).The financial loss due to injury can be vast, and was for example reported to be over £70 million in English professional league clubs during the 1999/2000 season (Woods, Hawkins, Hulse, & Hodson, 2002).

In particular, Anterior Cruciate Ligament (ACL) injuries have been of great concern over the past few decades, with reported incidence ranges from 0.06 to 2.07 per 1000 h of active soccer training and matches (Agel, Evans, Dick, Putukian, & Marshall, 2007; Bjordal, Arnly, Hannestad, & Strand, 1997). A recent study reported that approximately 200,000 ACL reconstructions are performed annually in the United States, with an average cost of $20,000 (~ £13000) per surgery, which translates into an estimated annual cost of $4 billion (£2.6 billion) for surgical procedures alone (Brophy et al., 2009). The consequences of ACL injury include multiple negative health concerns, including effects on academic achievement and psychological wellbeing (Freedman, Glasgow, Glasgow, & Bernstein, 1998), as well early onset of osteoarthritis, damage to knee menisci and chondral surfaces, and decreased activity levels due to functional instability (Yu & Garrett, 2007).

The majority of ACL injuries are non-contact in nature and take place during dynamic movements such as jumping, landing or suddenly changing directions (e.g., side cutting), rather than while interacting with other players (Fauno & Wulff Jakobsen, 2006). A variety of risk factors can be attributed to the occurrence of such non-contact ACL injuries in soccer (Alentorn-Geli et al., 2014a; Alentorn-Geli et al., 2009). These factors need to be considered when developing effective injury screening and injury prevention programmes. Among the risk factors, biomechanical and neuromuscular are considered modifiable and are of particular interest for prevention and intervention programmes.

Improper movement mechanics have been reported to place significant load on the ACL (Besier, Lloyd, Cochrane, & Ackland, 2001; Withrow, Huston, Wojtys, & Ashton-Miller, 2008). In addition, a reduction in hamstrings and quadriceps strength and muscle strength imbalance between the hamstrings and quadriceps also has been recognised as a risk factor for ACL injury in soccer (Soderman, Alfredson, Pietila, & Werner, 2001). Another important observation in soccer matches is that most injuries are most frequent during the latter stages of match-play (Ekstrand, Hagglund, & Walden, 2011; Hawkins et al., 2001). This coincides with observed reductions in physical performance (Bangsbo, Norregaard, & Thorso, 1991; Mohr, Krustrup, & Bangsbo, 2003) and suggests that exertion induced by match-play may further increase the risk of injury associated to altered movement mechanics (Greig, 2009; Sanna & O'Connor, 2008) and impaired muscle strength (Cohen, Zhao, Okwera, Matthews, & Delextrat, 2014; Delextrat, Baker, Cohen, & Clarke, 2011; Delextrat, Gregory, & Cohen, 2010; Greig, 2008; Rahnama, Reilly, Lees, & Graham-Smith, 2003; Small, McNaughton, Greig, & Lovell, 2010).

A considerable body of research has observed how high intensity and short-term fatigue protocols that induce high levels of exertion can alter lower limb mechanics

(Borotikar, Newcomer, Koppes, & McLean, 2008; Chappell et al., 2005; Cortes, Quammen, Lucci, Greska, & Onate, 2012; Lucci, Cortes, Van Lunen, Ringleb, & Onate, 2011; McLean et al., 2007; Tsai, Sigward, Pollard, Fletcher, & Powers, 2009) and muscle strength imbalance (Sangnier & Tourny-Chollet, 2007). However, these protocols do not represent the level of exertion and activity profile as occurs during soccer match-play. Others have therefore attempted to examine the effects of exertion induced by soccer match-play on biomechanical (Greig, 2009; Sanna & O'Connor, 2008) and muscle strength imbalance (Cohen et al., 2014; Delextrat et al., 2011; Delextrat et al., 2010; Greig, 2008; Rahnama et al., 2003). However, these studies have for various reasons struggled to recreate both the physiological responses and mechanical loading of match-play with an ecologically valid match-play simulation protocol. At present, whether any of these simulations adequately recreates soccer match-play to investigate the influence of match-play on biomechanical and muscle strength imbalance related markers of ACL injury remains unknown.

Substantial research efforts towards the goal of preventing ACL injuries have been undertaken in recent years, as the benefit of those can have widespread health and economic implications. Broadly speaking, studies can be classified into three types of studies, largely following the principles of the sports injury prevention framework as outlined in Finch (2006). Namely, there are those studies that determine the characteristics of ACL injury occurrences, those that identify injury risk factors, and those that develop prevention strategies. The work presented in this thesis will address the latter two types of studies, in an attempt to advance our understanding of how match-play affects certain ACL risk factors, and whether a half-time intervention could offset such effects. The significance of the presented work will be to add to the current understanding key modifiable markers of ACL injury in soccer. By observing the effects of soccer match-play simulation on biomechanical and muscle strength imbalance, the underlying principles of ACL injury risk in soccer may be revealed. Finally, this knowledge can form the foundations for developing more effective injury prevention strategies.

1.2 Aim and objectives

The overall aim of the research described in the present thesis was to investigate the effect of exertions induced by soccer match-play simulations on biomechanical and muscle strength markers of ACL injury risk, and to identify needs and opportunities for injury prevention programmes.

Specifically, the objectives underpinning the different studies were:

i. To demonstrate the differences and similarities in physiological response between overground and treadmill match-play simulation.
ii. To demonstrate the effects of treadmill versus overground soccer match-play simulation on biomechanical and muscle strength markers of ACL injury in both male and female soccer players.
iii. To demonstrate the temporal changes in biomechanical markers of ACL injury risk during a soccer match-play simulation.
iv. To demonstrate the impact of a half-time re-warmup intervention on those temporal changes in biomechanical and muscle strength markers of ACL injury risk during a soccer match-play simulation.

Chapter 2

Literature Review

2.1 Introduction

The following literature review will first focus on some epidemiologic evidence around non-contact ACL injuries in soccer and the proposed mechanisms of injury. It will then address lower extremity mechanics and muscle strength imbalance as markers of ACL injury risk, and how previous studies have demonstrated that exertion in terms of repetitive physical exercises can have an impact on them. The focus will subsequently go to soccer-specific match-play simulations as one particular type of repetitive exercise. These match-play simulations have been designed to recreate the physiological responses, movement demands and work rate profiles of match-play, and should allow us to investigate the effect of match-play on the selected markers of ACL injury risk. Finally, injury prevention programmes specifically in soccer will be reviewed. Whilst the literature review aims to provide an overview of the existing knowledge base, it is by no means intended to provide a fully comprehensive record of the large amount of research done on these topics.

2.2 Epidemiology of non-contact ACL injuries in soccer

Studies found that more than 70% of ACL ruptures in sports are caused by a non-contact mechanism (Boden, Dean, Feagin, & Garrett, 2000; Griffin et al., 2000). Similar findings reported in soccer that more than 58% of ACL injuries are caused without any physical contact with other players at the time of injury (Fauno & Wulff Jakobsen, 2006; Walden, Hagglund, Magnusson, & Ekstrand, 2011).

The reported incidence of ACL injury ranges from 0.06 to 2.07 per 1000 h of active soccer training and matches (Agel et al., 2007; Bjordal et al., 1997). A review by

Walden, Hagglund, Werner, and Ekstrand (2011) reported the ACL injuries to be much higher (range 7-65 times) during soccer match-play compared to training.

Female athletes have a higher incidence of ACL injuries than their male counterparts. Arendt and Dick (1995) found an average ACL injury rate of 0.31 per 1000 h of active soccer participation in females compared to 0.13 per 1000 h of active soccer participation in males. This was confirmed in another study that again reported higher incidence rates of 0.10 per 1000 game hours in females, compared to 0.057 per 1000 game hours in males (Bjordal et al., 1997). The increased participation and increased risk of injury in females has led to a substantial focus on ACL injury risk in female athletes in particular. Nevertheless, the socio-economic impact of ACL injuries is vast in both sexes, warranting research in both male and female populations.

It has been well established that most injuries in soccer tend to occur at a greater rate in the latter stages of match-play (Ekstrand et al., 2011; Hawkins et al., 2001). These findings suggest that exertion induced by soccer match-play may be a potential predisposing factor of ACL injury. An overview on the influence of exertions induced by soccer match-play on markers of injury risk will be the focus of this chapter and will be addressed in the later part of this chapter.

2.3 Mechanisms of non-contact ACL injuries in soccer players

Numerous mechanisms of ACL injury in soccer have been suggested over the past decades. Changes of direction or cutting manoeuvres combined with deceleration, landing from a jump in or near full extension, or pivoting with the knee near full extension and a firmly planted foot, are among the most common playing situations in soccer precluding a non-contact ACL injury (Alentorn-Geli et al., 2009; Boden et al., 2000; Fauno & Wulff Jakobsen, 2006). Boden et al. (2000) using retrospective video analysis reported a lower extremity alignment associated with ACL injury in which the tibia was externally rotated, the knee was close to full extension, and the foot was planted firmly on the surface during initial deceleration. They also observed valgus collapse or medial knee displacement at the knee. These alignments and movements are reported to involve knee valgus/varus (abduction/adduction) motion, internal/external rotation moments, and high anterior translation forces to the lower limb, as reviewed in various papers (Alentorn-Geli et al., 2009; Boden, Torg, Knowles, & Hewett, 2009; Hewett, Torg, & Boden, 2009). The anterior translation force, specifically at extension angles around 20-30°, may be the most isolated force associated with straining the ACL, and is often identified as a contributing factor to ACL injury mechanisms (Alentorn-Geli et al., 2009; Boden et al., 2000; Markolf et al., 1995; Yu & Garrett, 2007). However, a cadaver study suggested a combination of forces produces a higher strain on the ACL than isolated motions and torques (Berns, Hull, & Patterson, 1992).Thus, isolated knee valgus/varus motion or internal/external rotations do not strain the ACL to the magnitude of combined motions and torques such as an anteriorly directed translation added to valgus and/or internal rotation (Berns et al., 1992; Markolf et al., 1995). These observations have led to studies investigating tasks that potentially challenge the ACL as well as inducing multi-planar loads to the knee, in order to better understand various risk factors that put the ACL under increased stress.

2.4 Risk factors of non-contact ACL injury

Understanding risk factors is a key component of preventing non-contact ACL injuries. Risk factors for ACL injury have been categorised into external (also referred to as extrinsic) and internal (or intrinsic) factors, and a variety of these factors have been investigated and reviewed (Alentorn-Geli et al., 2009; Dai, Herman, Liu, Garrett, & Yu, 2012a; Shultz et al., 2012; Smith et al., 2012a, 2012c). Proposed external risk factors include type of competition, footwear and surface, and environment conditions. Proposed internal risk factors include, anatomical, hormonal, genetic, neuromuscular and biomechanical risk factors. Among the proposed internal risk factors, neuromuscular and biomechanical related factors can be modified through less intrusive intervention than for example anatomical and hormonal, offering opportunities for potentially cost-effective prevention of ACL injuries. Therefore, aspects associated to neuromuscular and biomechanical risk factors discussed in recent studies will be the primary focus in this review. However, an important consideration needs to be addressed first around the predictive strength associated to risk factors.

The strongest evidence to support the value of an experimental observation as predictor of injury is provided through a prospective cohort study i.e., by observing players that will sustain an injury and comparing them against healthy controls. From here onwards, we will refer to observations that have been demonstrated through prospective study as being predictive of injury through using the term *risk factor*. On the other hand, substantial evidence can stem from associative study, i.e., by associating surrogate observation to known risk factors, i.e., retrospectively observing differences between injured and uninjured or between high risk and low risk populations. From here onwards, such associative or retrospective evidence will be referred to by using the term *marker of injury risk*.

2.4.1 Biomechanical risk factors and markers of injury risk

At the time of this literature review, only one prospective study has been reported to determine biomechanical ACL risk factors, and that in female athletes (Hewett et al., 2005). Two hundred five female adolescent athletes (soccer, basketball and volleyball) were observed for a jump-landing task and then were followed for 13 months. During follow up, 9 athletes had a non-contact ACL injury. Compared with the uninjured athletes, they found that the injured athletes had an 8.4° larger knee abduction angle at initial contact, a 7.6° greater knee abduction at maximum flexion, a higher peak knee abduction moment (-45.3 vs. -18.4 N·m), and greater peak vertical ground reaction forces (1266.1 vs. 1057.8 N). The knee abduction moment predicted ACL injury status with 73% specificity and 78% sensitivity. While several aspects of this study are consistent with prior evidence, it is limited to females of a relatively narrow age group and level of participation, and most importantly, based on a relatively small number of injuries. The evidence supporting these parameters as risk factors of ACL injury is therefore rather narrow. Following this study, however, a considerable amount of studies have been conducted in which the outcomes of this study were taken forward. Particularly, the notion of increased knee extension at initial contact and increased external abduction moments during initial weight acceptance have gained considerable support as markers of ACL injury risk.

Previous findings support a sagittal plane injury mechanism of ACL injury related to increased knee extension angles during landing (Quatman, Quatman-Yates, & Hewett, 2010). Several studies found that a more extended knee induced greater ACL loading (Blackburn & Padua, 2008; Li, Defrate, Rubash, & Gill, 2005; Lin et al., 2009; Markolf et al., 1995). In addition, video observational studies (Boden et al., 2000; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007) demonstrated that during injury events, the knee angle is more extended with values between 0° and 30°.

During sagittal plane movements at the knee joint, the quadriceps muscle contractions produce anterior shear force at the proximal end of the tibia through the patellar tendon (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004). An in vitro study (Markolf et al., 1995) has demonstrated that an anterior shear force applied at the proximal tibia is the primary contributor to the ACL loading, and it has been theorised that a powerful quadriceps force at greater knee extension angles could produces enough anterior shear force at the tibia to cause ACL rapture (Li et al., 1999; Yu, Lin, & Garrett, 2006). The influence that quadriceps force has on ACL loading can be mediated by factors related to knee extension angle which are ACL elevation angle, patellar tendon insertion angle and hamstrings (biceps femoris) insertion angle (Blackburn & Padua, 2008)(Figure 1).

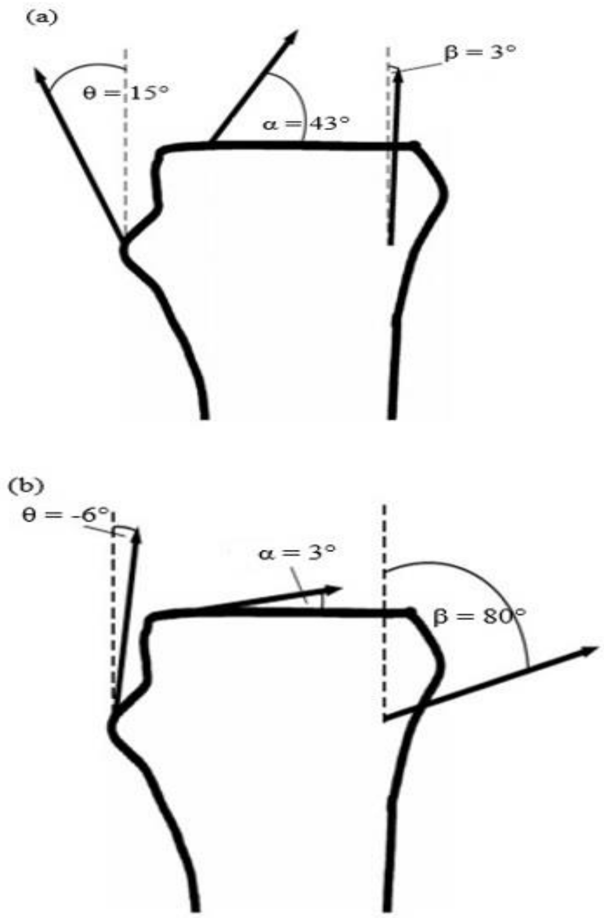

Figure 1. (a) Greater knee extension angle (more extended) at initial contact (9°) during erect landing condition and (b) more flexed knee angle at mean peak flexion angle (91°) during flexed landing condition. θ Patellar tendon insertion angle; β hamstrings insertion angle; α ACL elevation angle. Adapted with permission from Blackburn and Padua (2008).

The ACL elevation angles can be defined as the angle between the longitudinal axis of the ACL and the tibial plateau (Li et al., 2005). The resultant force along the longitudinal axis of the ACL equals the anterior shear force on the ACL divided by the cosines of the ACL elevation (McLean, Huang, Su, & Van Den Bogert, 2004). When the knee is more extended, the ACL elevation angle increases and the anterior tibial force produced by the quadriceps /patellar tendon on the ACL has a greater shear component (Figure 1 a) compared to a flexed knee (Figure 1 b), resulting a greater ACL loading.

In addition, the more extended knee angles during landing may increase the patellar tendon insertion angle that increases the anteriorly directed component of the quadriceps force (Nunley, Wright, Renner, Yu, & Garrett, 2003; Yu & Garrett, 2007). As the knee progresses into more extension, the patellar tendon insertion angle with respect to the tibial longitudinal axis increases (Zheng, Fleisig, Escamilla, & Barrentine, 1998). This change has an influence on the tibial shear force, as the anteriorly directed component of the quadriceps/patellar tendon force is increased (Blackburn & Padua, 2008). Thus, with a more extended knee during landing, the quadriceps exerts a higher anteriorly directed force that needs to be counteracted by both the ACL and the hamstrings. Lastly, when the knee is more extended, the angle of insertion of the hamstrings with respect to the tibial longitudinal axis decreases such that the hamstrings' potential to counteract anterior tibial force to the ACL is limited (Pandy & Shelburne, 1997) and may produce less impact absorption (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003). These findings combined suggest that a more extended knee extension angle during landing may be an important biomechanical marker for sustaining non-contact ACL injuries.

Considering the gender bias observed with non-contact ACL injury, studies have often attempted to identify markers of injury risk by comparing movement patterns between male and female athletes, and suggesting that differences may well explain the greater incidence of ACL injuries in female athletes. These studies observed that female recreational athletes are prone to perform sport-specific dynamic tasks (e.g., side cutting, landing, sudden deceleration) with significantly different movement and loading patterns in all three planes of motion. Kinematic observations include greater knee extension angles (Chappell et al., 2005; McLean, Huang, & Van Den Bogert, 2005; McLean, Lipfert, & van den Bogert, 2004; Yu et al., 2006), greater knee valgus angles (Ford, Myer, & Hewett, 2003; McLean, Lipfert, et al., 2004), and greater hip rotation angles (Pollard, Sigward, & Powers, 2007). Kinetic observations identified greater joint loading at the knee in females, primarily in terms of greater knee abduction moments (Chappell, Yu, Kirkendall, & Garrett, 2002; Sigward & Powers, 2006; Yu et al., 2006). When these observations concurred with stress inducing mechanisms from in vitro observations (cadaver studies), then authors often suggested that this could explain an increased risk of injury in females. Despite these insights on lower extremity biomechanics during sport-specific dynamic tasks and the observed gender variations, the relative importance of these biomechanical characteristics in terms of injury risk remain unknown unless prospective study allowed to identify the predictive strength of any of those parameters.

2.4.2 Muscle strength and muscle imbalance related risk factors and markers of injury risk

Developing lower limb strength and that especially for hamstrings and quadriceps muscles is one of the important ingredients in training for soccer. During performing athletic tasks such as landing and cutting, the absence of adequate strength will result in impaired lower-extremity mechanics that likely place an athlete at risk for injury. Muscle strength deficiency, in particular eccentric hamstring strength (H_{ecc}), has recently received substantial research attention, as eccentric muscle actions have been found to be an integral part of the functional repertoire of the muscles and a key factor associated to

ACL injury (Tsepis, Vagenas, Giakas, & Georgoulis, 2004). In soccer, eccentric hamstrings contractions are important during kicking and sprinting, where the hamstrings act eccentrically to decelerate the tibia during rapid and explosive knee extensions (Bruckner & Khan, 2012; Sun, Wei, Zhong, Fu, & Liu, 2015). Furthermore, their reduced capacity to decelerate the movement of the thigh at the same time impedes their capacity to counteract the anterior shear forces created by strong quadriceps contractions. The increased anterior shear forces would place more stress on the ACL.

Muscle imbalance between the strength developed by hamstrings and quadriceps muscles also has been identified as a potential risk factor for ACL injury in soccer (Soderman et al., 2001). The most commonly reported muscle strength imbalance is by calculating a ratio of the hamstrings strength relative to quadriceps strength. The conventional method of this calculation is done by dividing maximal concentric hamstring (H_{con}) strength by the maximal concentric quadriceps (Q_{con}) strength obtained at a given angular velocity (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). A lower conventional H_{con}:Q_{con} ratio has been found to be related to a higher risk of ACL injury (Soderman et al., 2001). In addition, with the hamstrings acting in a synergistic role to the ACL through preventing anterior tibial translation, the risk of hamstring injuries was increased 17 times (Yeung, Suen, & Yeung, 2009) and a higher risk of non-contact lower extremity injury (Kim & Hong, 2011) when the conventional H_{con}:Q_{con} ratio value was below 0.60. However, the relevance of using H_{con}:Q_{con} ratio in sport has been questioned, since opposing muscles cannot develop simultaneous concentric contractions (Croisier, Forthomme, Namurois, Vanderthommen, & Crielaard, 2002).

Therefore, the functional H_{ecc} : Q_{con} ratio, which can be calculated by dividing maximal H_{ecc} strength by the maximal Q_{con} strength obtained at a given angular velocity (Aagaard et al., 1998), has been proposed to be more representatives to the muscle actions that occur in soccer (Delextrat et al., 2010). The functional H_{ecc} : Q_{con} ratio has an optimum range of 0.70 – 1.0, with studies suggesting that a higher H_{ecc} : Q_{con} ratio might serve to protect individuals from ACL injuries (Aagaard et al., 1998; Hewett, Myer, & Ford, 2001).

Recently, a few studies have started to investigate the effect of soccer match simulation on angle of peak torques (Cohen et al., 2014; Small et al., 2010). These studies have observed a shift in H_{ecc} angle of peak torque towards the shorter length after 90 min of soccer match simulation. This finding has been proposed to increase susceptibility to injury as the peak torque generation at a shorter optimum muscle length means that more of the muscle operating range would be on the descending limb of the length-tension curve (Brughelli & Cronin, 2007). In addition, coupled with a reduced H_{ecc} strength, this can lead to increased anterior tibial translation, indicative of reduced knee stability and increased vulnerability to ACL injury (Myer et al., 2009). Small et al. (2010) found that Q_{con} and H_{con} shifted in the optimum length for peak torque in the direction of longer muscle lengths due to match-play simulation, which they suggested was potentially a consequence of a greater loss of relative force at shorter muscle lengths.

2.4.3 Effect of fatigue on biomechanical and muscle strength related markers of ACL injury risk

It has been well established that injuries in soccer tend to occur at a greater rate in the later stages of match-play. This has been suggested to occur due to players experiencing high levels of exertion, proposing that exertion induced by soccer match-play may be a potential predisposing factor of injury. The high level of exertion of sustained physical exercise can induce a reduction of maximal force or power to which people have referred to as *fatigue*, that is, referring to a decline in performance (Taylor, Butler, & Gandevia, 2000). Fatigue has been considered to be a factor contributing to increased ACL injury risk, not only due to reduced maximal force, but also due to decreased knee proprioception or increased joint laxity (Hashemi et al., 2011; Rozzi, Lephart, & Fu, 1999). Fatigue has actually been proposed as a necessary prerequisite to provide the condition of an injury inciting event (Hashemi et al., 2011). It has also been reported that fatigue alters lower limb biomechanical and neuromuscular factors during dynamic tasks, alterations that have been suggested to increase injury risk (Borotikar et al., 2008; Chappell et al., 2005; Cortes et al., 2012; McLean et al., 2007). An overview of these studies and their key findings is provided in Table 1. In tasks requiring a rapid deceleration, also a delayed onset of quadriceps and hamstrings activation is expected to lead to a decrease in knee flexion at initial contact, and this is expected to cause a decrease in shock absorption and knee stability during landing (Chappell et al., 2005). This decrease in knee stability has been suggested as an ACL injury risk as it has been suggested that frontal plane knee stability protects against excessive knee abduction or adduction loading (Hewett et al., 2005).

Table 1. Summary of studies on the effect of fatigue on biomechanical markers of ACL injury risk

Author, Year	Subjects Type/n	Gender/ Age	Fatigue Protocol / Tasks	Dependent Variable	Findings
Chappell et al. (2005)	Amateur sports athletes n = 20	Male (10) 24y Female (10) 22y	Unlimited repetitions of 5 x vertical jumps followed by a 30-m sprint Stop-jump task (forward, vertical, backward) DL and NDL	Knee kinetics and kinematics	↑ Peak proximal tibial anterior shear forces ↑ Peak knee abduction moments ↑ Knee extension angle
McLean et al. (2007)	University sports athletes n = 20	Male (10) Female (10)	Series of fast 20 cm box step-up movements, continuous 6 m plyometric bounding 50 cm box drop DL and NDL	Ankle, knee and hip kinetics and kinematics	↑ Ankle dorsiflexion moments ↑ Peak knee abduction moments and angles ↑ Knee internal rotation moments and angles
Borotikar et al. (2008)	University sports athletes n = 25	Female 21y	Continues set of 5 double leg squats between jump trial Single leg landing DL and NDL	Ankle, knee and hip kinematics	↑ Ankle supination angles at peak stance ↑ Knee abduction angles at peak stance ↑ Knee internal rotation angles at peak stance ↑ Hip extension angle at IC ↑ Hip internal rotation angle at IC
Tsai et al. (2009)	Recreatio nal athletes n = 15	Female 26y	Similar to Chappell et al. (2005) 45° side cutting DL	Knee kinetics and kinematics	↑ Peak knee abduction moments and angles ↑ Knee internal rotation angles

DL dominant limb; NDL non-dominant limb; IC initial contact

Similarly, high levels of fatigue also have been found to impair muscle strength in soccer players, especially in the strength of hamstrings compared to the quadriceps (Sangnier & Tourny-Chollet, 2007). By using an isokinetic endurance test (50 repetitions of flexions-extensions at 180° $\cdot s^{-1}$ in concentric mode) as part of a fatigue protocol, this study observed a greater reduction in hamstrings strength which was also affecting the balance of strength (H_{con}:Q_{con} ratio of 0.49) between hamstrings and quadriceps, and may have affected the stabilising function of the knee.

Alterations in muscle strength imbalance and in lower extremity mechanics due to fatigue are likely interrelated, yet previous work has often focused on one or the other separately. Also, match-play involves a series of activities requiring a particular type of physical effort, which has been simulated in various ways. Therefore, in the following paragraph, existing literature on soccer match-play simulation will be reviewed (Section 2.5), followed by a review of the literature observing how soccer match-play simulation may affect markers of ACL injury risk (Section 2.6).

2.5 Simulating the effects of soccer-match play

Research has focused largely on two types of protocols to simulate the effects of match-play. First, there are protocols that focus on inducing fatigue itself, similar to what was described in the previous section. For those protocols the primary effect of fatigue is typically induced by short duration high intensity repetitions of a few types of movements, likely leading to a highly localised reduction in power generating capacity (e.g. those muscles involved with main force generation during the chosen movements). For these protocols, the effectiveness of the protocol to induce a certain level of fatigue is controlled by measuring the reduction in force/power generating capability. Second, there are protocols that focus on closely mimicking the task profile of match-play, in which fatigue is a secondary effect of the match-play simulation. These protocols involve intermittent intensity repetitions of a larger variety of movements as experienced during match-play, simulating one or two playing periods. Key literature on both types of protocols will be discussed separately here.

2.5.1 Protocols that induce soccer-specific fatigue

Table 2 summarises the protocols used to induce soccer-specific fatigue. These short-term high intensity protocols were developed to highlight a decline in physical performance, probably as a consequence of an acute effect of temporary fatigue, which was found during soccer matches (Mohr et al., 2003). The first protocol was developed by Rampinini et al. (2008) to investigate the effects of fatigue on short passing ability in young soccer players. Participants were instructed to perform a 5 min simulation with a high intensity and low intensity ratio of 1:3 using shuttle running at various speeds following an audio signal. The second protocol which was known as the functional agility short-term fatigue protocol (FAST-FP) was established by combining various agility movements in order to mimic multiple direction-changing and sprinting patterns that a soccer player would endure during a competitive match. It was developed by Lucci et al. (2011) and involved short term (approximately 5 min) high intensity agility sprints (L-drill), countermovement jumps, and agility ladder running. This protocol has been used in other studies to investigate the influence of fatigue on biomechanical markers of ACL injuries (Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013; Cortes et al., 2012; Quammen et al., 2012).

Table 2. Summary of soccer-specific fatigue protocols

Author, Year	Subjects Type/n	Gender/ Age	Protocol	Activity Profiles	HR (beats·min^{-1}) / RPE
Rampinini et al. (2008)	Junior (pro team) soccer players n = 16	Male 18y	High intensity simulation (HIS) Duration: 5 min	10 (5 x 16 km·h^{-1} and 5 x 19 km·h^{-1}) x 40 m shuttle running Recovery phase (alternate) Standing (0 km·h^{-1}, Walking (5 km·h^{-1}, Jogging (7 km·h^{-1})	HR_{max}: 89 ± 6 % RPE (scale 1-10): 6.6 ± 1.3
Lucci et al. (2011)	University soccer players n = 15	Female 19y	Functional agility short-term fatigue protocol (FAST-FP) Duration: 5 min	30 cm box step up L-drill 5 x counter movement jumps Agility ladder (forward or sideways)	HR_{max}: 90 ± 4 % RPE: N/A

HR heart rate; HR_{max} maximal heart rate; RPE rate of perceived exertion

2.5.2 Protocols that mimic match-play

Several soccer-specific match-play simulations exist to assess physiological and mechanical responses to intermittent exercise. The direct approach to evaluating the soccer-specific physiological and mechanical demands related to injury is by monitoring responses to actual match-play. However, the constraints of carrying out detailed physiological and mechanical assessment as well as ensuring appropriate experimental control of the environment is difficult. These limitations have resulted in the development of soccer match-play simulations, attempting to mimic the activity profiles observed in actual matches whilst retaining control over key experimental variables (e.g., intensity, duration). This approach may provide better understanding of the soccer-specific demands, its relationship with markers of injury risk, and allows the potential of prevention programmes to be evaluated under adequately controlled experimental condition. These soccer match-play simulations have been delivered using either treadmill or overground locomotion.

2.5.2.1 Treadmill based match-play simulation

A comprehensive overview of the various studies in which treadmill based soccer match-play simulations were applied is provided in Table 3. The most frequently used protocols will be highlighted here. The first ones to develop a treadmill based simulation were Drust, Reilly, and Cable (2000). They developed a soccer match simulation by utilising a motorised treadmill based on the motion-analysis data from Thomas and Reilly (1976). This protocol was originally designed to last for a duration of 46 min, although it has been adapted to simulate a full 90 min game including a 15 min half time recovery period (Clarke, Maclaren, Reilly, & Drust, 2011; Rahnama et al., 2003). Activities incorporated in the protocol include static pauses, walking, jogging, cruising and sprinting in proportions similar to those observed in match-play. However, this protocol required the participant to spend a substantially greater amount of time performing the high intensity activities, totally over 50% of the total distance covered compared with 16% observed during 45 min actual matches (Thatcher & Batterham, 2004). In addition, the players completed a total distance in excess of 18 km during the 90 min simulation which is substantially further than the 10 – 12 km covered during 90 min match-play (Stolen, Chamari, Castagna, & Wisloff, 2005).

Greig, McNaughton, and Lovell (2006) developed a soccer-specific intermittent protocol based on a notational analysis (Bangsbo, 1994) categorising 8 modes of activities which included standing, walking, jogging, low speed, moderate speed, high speed and sprinting. The 15 min intermittent activity profile is completed 6 times in the 90 min test, with a 15 min half time interval. The activity profile resulted in a total distance covered of 9.72 km, which is slightly less than the average distance covered in a match.

The benefit of treadmill based match-play simulations is that they require limited space (e.g. inside an environmental chamber), or that it allows the researcher to make observations whereby the player is connected with wires to equipment (e.g. oxygen consumption tests). However, treadmill based simulation either generates insufficient physiological response, e.g. Greig et al. (2006), or requires the incorporation of additional high intensity running activity, e.g. Drust et al. (2000), to achieve the physiological responses as observed during match-play (Bangsbo, 1994e; Thomas & Reilly, 1976). This makes treadmill based simulation potentially less ecologically valid. Additionally, treadmill based simulation may well be ecologically less valid considering that it only involves straight locomotion, rather than the more extensive task make-up of a real match involving multi-directional movements.

Table 3. Summary of studies describing treadmill based soccer-match simulation

Author, Year	Subjects Type/n	Gender/ Age	Protocol	Activity Profiles	HR (beats·min^{-1}) / RPE
Drust et al. (2000)	University soccer players n = 7	Male 24y	Soccer specific intermittent protocol based on match analysis data from Thomas and Reilly (1976) Duration: 46 min 11 s	Standing (0 km·h^{-1}) Walking (6 km·h^{-1}) Jogging (12 km·h^{-1}) Cruising (15 km·h^{-1}) Sprinting (21 km·h^{-1})	HR: 168 ± 10 RPE (scale 6-20): 15 ± 2
Rahnama et al. (2003)	Amateur soccer player n = 13	Male 23y	Soccer specific intermittent protocol (Drust et al., 2000) based on match analysis data from Thomas and Reilly (1976) Duration: Over 90 min [22 min in duration separated by a 1 min static rest x 2; 15 min interval (half time)]	Standing (0 km·h^{-1}) Walking (6 km·h^{-1}) Jogging (12 km·h^{-1}) Cruising (15 km·h^{-1}) Sprinting (21 km·h^{-1})	HR: N/A RPE: N/A
Greig et al. (2006)	Semi-pro soccer players N = 10	Male 24y	Soccer specific intermittent protocol based on match analysis data from Bangsbo (1994e) Duration: Over 90 min [15 min x 6; 2 x 45 min with 15 min interval (half time)]	Standing (0 km·h^{-1}) Walking (4 km·h^{-1}) Jogging (8 km·h^{-1}) Running low speed (12 km·h^{-1}) Running moderate speed (16 km·h^{-1}) Running high speed (21 km·h^{-1}) Sprint (25 km·h^{-1})	HR: Increased from 125 ± 10 (first 15 min) to 135 ± 10 (last 15 min) RPE (scale 6-20): Increased from 9 ± 1 (first 15 min) to 12 ± 2 (last 15 min)
Clarke, Drust, Maclaren, and Reilly (2008); Clarke et al. (2011)	University soccer players N = 12	Male 24y	Modified soccer specific intermittent protocol (Drust et al., 2000) Duration Over 90 min [15 min x 6; 2 x 45 min with 15 min interval (half time)]	Standing (0 km·h^{-1}) Walking (4 km·h^{-1}) Jogging (12 km·h^{-1}) Cruising (15 km·h^{-1}) Sprinting (19 km·h^{-1})	HR: 159 ± 6 RPE (scale 6-20): 13 ± 1

HR heart rate; RPE rate of perceived exertion

2.5.2.2 Overground match-play simulation

To improve ecological validity of the match-play simulation, several intermittent match simulations were developed to simulate a more comprehensive soccer activity profile involving overground locomotion (Lovell, Knapper, & Small, 2008; Nicholas, Nuttall, & Williams, 2000; Small et al., 2010). An overview of the various studies in which such overground soccer match-play simulations were applied is provided in Table 4.

The Loughborough Intermittent Shuttle Run Test (LIST) developed by Nicholas et al. (2000) is arguably the most widely used overground simulation (Delextrat et al., 2010; Kellis, Katis, & Vrabas, 2006; Sanna & O'Connor, 2008; Stone & Oliver, 2009). In this protocol, participants are required to run between two lines, 20 m apart, at various speeds related to estimated individual VO_{2max} values. The running and walking speeds during each 20 m of the test are dictated by an audio signal. The LIST protocol exists of two parts. Part A has a fixed duration and consists of five 15 min intermittent activity periods separated by 3 min of recovery. The exercise periods consist of a pre-determined pattern of intermittent activity (standing, walking, jogging, cruising and maximal sprint) that is based on motion analysis data (Drust, Reilly, & Rienzi, 1998). Part B is then designed to act as a performance test that would exhaust the subjects within approximately 10 min. The participants are required to run at speeds corresponding to 55% and 95% of predicted $V02_{max}$, the speed alternating every 20 m. This pattern of exercise is repeated continuously until the participants are no longer able to maintain the required speed for two consecutive shuttles at the higher of the two exercise intensities. Some studies have modified the LIST for their own specific research objectives. Delextrat et al. (2011) for example modified the LIST by replacing the final min of each 15 min period with six shots at goal. The main reason for this modification was to reproduce more closely the movement activity experienced in soccer.

The soccer-specific aerobic field test (SAFT^{90}) is another overground simulation, initially developed by Lovell et al. (2008). This simulation is based on the contemporary time-motion analysis data obtained from 2007 English Championship Level match-play (Prozone®). The simulation was designed to replicate the physiological response of soccer match-play (Lovell et al., 2008; Small, McNaughton, Greig, & Lovell, 2009; Small et al., 2010; Small, McNaughton, Greig, Lohkamp, & Lovell, 2009). The SAFT^{90} simulation includes multidirectional and utility movements, and frequent acceleration and deceleration as is inherent to match play. The design of the SAFT^{90} course was based around a shuttle run over a 20 m distance, with the incorporation of four positioned poles for the participants to navigate using utility movements. The course is performed with the participants performing either backwards running or side-stepping around the first field pole, followed by forwards running through the course, navigating the middle three field poles. The movement intensity and activity performed by the participants whilst completing the overground course is maintained using verbal signals on an audio recording. A 15 min activity profile was developed and this is repeated 6 times during the 90 min simulated soccer match. No contact actions such as kicking or tackling are performed.

Table 4. Summary of studies describing overground soccer-match simulation

Author, Year	Subjects Type/n	Gender/ Age	Protocol	Activity Profiles	HR (beats·min^{-1}) / RPE
Nicholas et al. (2000)	Amateur soccer and rugby players n = 7	Male 22y	Loughborough intermittent shuttle test (LIST) Duration: Over 90 min (Part A: 15 min x 5 separated by 3 min recovery; Part B: ~10 min intermittent shuttle running to exhaustion)	Standing (0 km·h^{-1}) Walking (individual walking phase) Jogging (55% of individual VO_{2max}) Cruising (95% of individual VO_{2max}) Sprinting (maximal speed)	HR:~170 ± 4 RPE (scale 1-10): Increased from ~3 to 8 (after 75 min) and 10 (at exhaustion)
Sanna and O'Connor (2008)	University soccer players n = 12	Female 20y	Intermittent shuttle run (ISR) Duration: 60 min (15 min x 3separated by 3 min recovery and a final block of 10 min)	Standing (0 km·h^{-1}) Walking (35% of individual VO_{2max}) Jogging (55% of individual VO_{2max}) Cruising (95% of individual VO_{2max}) Sprinting (maximal speed)	HR:~170 ± 4 RPE (scale 1-10): Increased from 3 ± 1 (after 15 min) to 6.8 ± 1.1 (final 10 min)
Small et al. (2010)	Semi-pro soccer players n = 16	Male 21y	Soccer-specific aerobic field test (SAFT^{90}) based on match analysis data from 2007 English Championship Level match-play (Prozone ®) Validated by Lovell et al. (2008) Duration: Over 90 min [2 x 45 min with 15 min interval (half time)]	Standing (0 km·h^{-1}) Walking (5 km·h^{-1}) Jogging (10.3 km·h^{-1}) Striding (15 km·h^{-1}) Sprinting (>20.4 km·h^{-1})	HR: N/A RPE: N/A
Williams, Abt, and Kilding (2010)	Amateur players n = 15	Male 26y	Ball-sport endurance and sprint test ($BEAST_{90}$) based on match analysis data (Bangsbo et al., 1991; Mayhew & Wenger, 1985; Reilly & Williams, 2003) Duration: 90 min [2 x 45 min with 15 min interval (half time)]	Walking Jogging/decelerating Forward running Backward jogging Sprinting (75% of maximum effort) Jumping Target shooting	HR: Range from 156 to 167 RPE: N/A
Bendiksen et al. (2012)	Amateur soccer players n = 12	Male 24y	Copenhagen Soccer Test (CST) based on match analysis data (Mohr et al., 2003) Duration: 90 min [2 x 45 min with 15 min interval (half time)]	Standing (0 km·h^{-1}) Walking (6 km·h^{-1}) Jogging (8 km·h^{-1}) Low speed running (12 km·h^{-1}) Moderate speed running (15 km·h^{-1}) High speed running (18 km·h^{-1})	HR_{max}: range from 85 ± 1 % to 86 ± 1 % RPE: N/A

				Backward running (10 km·h[1]) Backward/sideways running (8 $km \cdot h^{-1}$) Sprinting (>25 $km \cdot h^{-1}$)	
Robineau, Jouaux, Lacroix, and Babault (2012)	Amateur soccer players n = 8	Male 20y	Soccer game modelling based on match analysis data from French First League Duration: 90 min [2 x 45 min with 15 min interval (half time)]	Standing (0 $km \cdot h^{-1}$) Walking (4 $km \cdot h^{-1}$) Low speed running (8,10,12 $km \cdot h^{-1}$) Moderate speed running (< 10% Maximal aerobic velocity [MAV], MAV, >10% MAV) Sprinting (maximal speed)	HR_{max}: 84 ± 6 % RPE: N/A
Cone et al. (2012)	University soccer players n = 24	Male (12) and Female (12) 20y	Individualised soccer-match simulation Duration: 90 min [2 x 45 min with 15 min interval (half time)]	Walking (20-39% maximal running speed) Jogging (40-59% maximal running speed) Low speed running (60-83% maximal running speed) Moderate speed running (84-94% maximal running speed) High speed running (105-109% maximal running speed)	HR: N/A RPE (scale 6-20): 15 ± 3
Lovell, Midgley, Barrett, Carter, and Small (2013)	Semi-pro soccer players n = 10	Male 21y	Soccer-specific aerobic field test ($SAFT^{90}$) based on match analysis data from 2007 English Championship Level match-play (Prozone ®) Validated by Lovell et al. (2008) Over 90 min [2 x 45 min with 15 min interval (half time)]	Standing (0 $km \cdot h^{-1}$) Walking (5 $km \cdot h^{-1}$) Jogging (10.3 $km \cdot h^{-1}$) Striding (15 $km \cdot h^{-1}$) Sprinting (>20.4 $km \cdot h^{-1}$)	HR: 161 ± 8 RPE: N/A

HR heart rate; HR_{max} maximal heart rate; RPE rate of perceived exertion

2.6 Effect of soccer-specific fatigue protocols on biomechanical and muscle strength related markers of ACL injury risk

Altered lower extremity mechanics have only been observed after short-term high intensity soccer-specific fatigue protocols (Table 5). These impairments are related to an erect knee and hip posture, and internal rotation during landing. To date, no published study has investigated the effect of soccer-specific fatigue protocols on muscle strength imbalance.

Table 5. Summary of studies on the effect of soccer-specific fatigue protocol on biomechanical related risk factor on markers of ACL injury risk

Author, Year	**Subjects Type/n**	**Gender/ Age**	**Match-Simulation / Tasks**	**Dependent Variable**	**Findings**
Lucci et al. (2011)	University soccer players n = 15	Female 19y	FAST-FP (Lucci et al., 2011) Unanticipated 45° side cutting DL	Knee and hip kinetics and kinematics	↑ Knee extension angle at IC (Pre: -25.6 ± 6.8° to Post: -22.4 ± 2.9°) ↑ Hip extension angle at IC (Pre: -36.4 ± 8.4° to Post: -30.4 ± 9.3°)
Quammen et al. (2012)	University soccer players n = 15	Female 19y	FAST-FP (Lucci et al., 2011) Unanticipated 45° side cutting or stop-jump DL	Knee and hip kinetics and kinematics (stop-jump task only)	↑ Knee extension angle at peak vertical ground reaction force (Pre: -50.4 ± 10.3° to Post: 44.7 ± 8.4°) ↑ Hip extension angle at peak vertical ground reaction force (Pre: -38.8 ± 5.03° to Post: -35.9 ± 6.5°) ↑ Hip extension angle at IC (Pre: -50.1 ± 9.5° to Post: -44.7 ± 8.1°)
Cortes et al. (2012)	University soccer players n = 15	Female 19y	FAST-FP (Lucci et al., 2011) Unanticipated 45° side cutting or stop-jump DL	Knee and hip kinetics and kinematics	↑ Knee internal rotation angle at IC (side cutting, Pre: 14.2 ± 6.2° to Post: 10.9 ± 5.6°; stop-jump, Pre:7.9 ± 7.8° to Post: Pre:11.9 ± 9.8°) ↑ Knee extension angle at peak posterior ground reaction force (side cutting, Pre: -34.2 ± 8.6° to Post: -31.2 ± 7.7°; stop-jump, Pre:-38.5 ± 5.5° to Post: Pre:-34.9 ± 6.7°) ↑ Knee extension angle at peak stance (side cutting, Pre: -53.1 ± 7.0° to Post: -48.3 ± 7.4°; stop-jump, Pre:-57.6 ± 8.9° to Post: Pre:-51.6 ± 10.1°)

DL dominant limb; NDL non-dominant limb; IC initial contact

2.7 Effect of soccer match-play simulations on biomechanical and muscle strength related markers of ACL injury risk

Whilst in Section 2.4.3 and 2.6, the effects of localised fatigue and soccer-specific fatigue were reviewed, here the focus will be on the few existing studies on the effect of exertions induced by soccer match-play simulation.

Two studies have attempted to investigate the effects of soccer-match exertion on knee joint mechanics, using either treadmill or an overground simulation (Table 6 a). Greig (2009) conducted a 90 min soccer match simulation with a motorised treadmill and observed a more extended knee at initial contact after 45 and 90 min, and after the half-time interval. In addition, Sanna and O'Connor (2008) utilised a 60 min overground soccer match simulation and observed a significant pre to post difference in knee internal rotation angles during a 45° side cutting manoeuvres. No significant changes in peak knee abduction moments were observed in any of these studies. Besides these studies, we are not aware of any studies to date that have provided evidence on the effect of soccer match-play simulation on biomechanical markers of ACL injury risk.

Various studies have also investigated the effects of soccer match simulation on muscle strength and imbalance (Table 6 b). Findings indicated that exertion induced by soccer match simulation in amateur and professional male players significantly reduces the conventional H_{con} : Q_{con} ratio by 3 – 10% (Rahnama et al., 2003). Even greater reductions were observed in the functional H_{ecc} : Q_{con} ratio, ranging from 13 – 30% (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Rahnama et al., 2003; Small et al., 2010). These reductions were observed at angular velocities of 60° $\cdot s^{-1}$, 120° $\cdot s^{-1}$, 180° $\cdot s^{-1}$ and 300° $\cdot s^{-1}$. These findings suggest that the functional H_{ecc} : Q_{con} ratio is more affected during match-play and more representative of muscular demands in soccer (e.g., kicking and sprinting). The reduced H_{ecc} : Q_{con} ratios were largely the result of a reduction in H_{ecc} strength, indicating that H_{ecc} strength are likely to be most affected during match-play. Only one study has investigated the changes in muscle strength and imbalance in female soccer players (Delextrat et al., 2011). They observed similar reduction in H_{ecc} strength (9 – 22%) and reductions in functional H_{ecc} : Q_{con} ratio (8 – 14%).

Recently studies have gained interest in how the angle of peak torque changes with match-play (Cohen et al., 2014; Small et al., 2010). They observed a shift in the angle of peak torque towards longer muscle lengths in Q_{con} and towards shorter muscle lengths in H_{ecc} during soccer match-play. The authors proposed that this could well be an important marker of ACL injury risk.

Table 6. Summary of studies on the effect of soccer match-play simulations on biomechanical (a) and muscle strength (b) related markers of ACL injury risk

Author, Year	**Subjects Type/n**	**Gender/ Age**	**Match-Simulation / Tasks**	**Dependent Variable**	**Findings**
			(a) Biomechanical		
Greig (2009)	Professional soccer players n = 10	Male 25y	Treadmill simulation (Greig et al., 2006) Anticipated 180° side cutting DL and NDL	Knee kinematics	↑ Knee extension angle at IC (Pre: -39.5 ± 6.3° to Post: -30.2 ± 2.9°) ↑ Knee varus alignment at IC (45 min: 4.7 ± 7.9° to Post: 6.9 ± 7.4°)
Sanna and O'Connor (2008)	University soccer players n = 12	Female 20y	ISR overground simulation (Sanna & O'Connor, 2008) Anticipated 45° side cutting DL	Ankle, knee and hip kinetics and kinematics	↑ Knee rotation angle at IC (Pre: -0.8 ± 4.9° to Post: -2.1 ± 7.3°) ↑ Knee rotation angle at stance phase (Pre: 13.7 ± 2.4° to Post: 17 ± 4.2°)
			(b) Muscle Strength		
Rahnama et al. (2003)	Amateur soccer player n = 13	Male 23y	Treadmill simulation (Drust et al., 2000) Isokinetic dynamometer Angular velocity: 60° $\cdot s^{-1}$, 120° $\cdot s^{-1}$, 300° $\cdot s^{-1}$ DL and NDL	Q_{con} PT H_{con} PT H_{ecc} PT H_{con}:Q_{con} ratio H_{ecc}:Q_{con} ratio	↓ Q_{con} PT at 60° $\cdot s^{-1}$ (DL 16%; NDL 13%) at 120° $\cdot s^{-1}$ (DL 8%; NDL 10%) at 300° $\cdot s^{-1}$ (DL 9%; NDL 7%) ↓ H_{con} PT at 60° $\cdot s^{-1}$ (DL 17%; NDL 16%) at 120° $\cdot s^{-1}$ (DL 15%; NDL 17%) at 300° $\cdot s^{-1}$ (DL 15%; NDL 12%) ↓ H_{ecc} PT at 120° $\cdot s^{-1}$ (DL 17%; NDL 18%) ↓ H_{con}:Q_{con} ratio at 60° $\cdot s^{-1}$ (NDL 3%) at 120° $\cdot s^{-1}$ (DL 10%) at 300° $\cdot s^{-1}$ (DL 6%) ↓ H_{ecc}:Q_{con} ratio at 120° $\cdot s^{-1}$ (DL 13%)

Greig (2008)	Pro soccer player N = 10	Male 25y	Treadmill simulation (Greig et al., 2006) Isokinetic dynamometer Angular velocity: $60° \cdot s^{-1}$, $180° \cdot s^{-1}$, $300° \cdot s^{-1}$ DL	Q_{con} PT H_{con} PT H_{ecc} PT H_{con}:Q_{con} ratio H_{ecc}:Q_{con} ratio	↓ H_{ecc} PT at $300° \cdot s^{-1}$ (31%) ↓ H_{ecc}:Q_{con} ratio at $180° \cdot s^{-1}$ (30%) at $300° \cdot s^{-1}$ (29%)
Delextrat et al. (2010)	University soccer players N = 8	Male 20y	LIST overground simulation (Nicholas et al., 2000) Isokinetic dynamometer Angular velocity: $60° \cdot s^{-1}$, $180° \cdot s^{-1}$ DL and NDL	Q_{con} PT H_{con} PT H_{ecc} PT H_{con}:Q_{con} ratio H_{ecc}:Q_{con} ratio	↓ Q_{con} PT at $60° \cdot s^{-1}$ (DL 17%; NDL 15%) at $180° \cdot s^{-1}$ (DL 14%; NDL 20%) ↓ H_{con} PT at $60° \cdot s^{-1}$ (DL 18%; NDL 24%) at $180° \cdot s^{-1}$ (DL 36%; NDL 26%) ↓ H_{ecc} PT at $60° \cdot s^{-1}$ (DL 31%; NDL 25%) at $180° \cdot s^{-1}$ (DL 26%; NDL 27%) ↓ H_{con}:Q_{con} ratio At $180° \cdot s^{-1}$ (DL 26%) ↓ H_{ecc}:Q_{con} ratio at $60° \cdot s^{-1}$ (DL 17%) $180° \cdot s^{-1}$ (DL 14%)
Small et al. (2010)	Semi-pro soccer players N = 16	Male 21y	SAFT^{90} overground simulation Isokinetic dynamometer Angular velocity: $120° \cdot s^{-1}$ DL	Q_{con} PT H_{con} PT H_{ecc} PT H_{con}:Q_{con} ratio H_{ecc}:Q_{con} ratio Q_{con} angle of PT H_{con} angle of PT	↓ H_{ecc} PT (17%) ↓ H_{ecc}:Q_{con} ratio (15%) ↑ Q_{con} angle of PT (5%) ↑ H_{con} angle of PT (26%) ↑ H_{ecc} angle of PT (26%)
Delextrat et al. (2011)	University soccer players N = 14	Female 26y	LIST overground simulation (Nicholas et al., 2000) Isokinetic dynamometer Angular velocity: $120° \cdot s^{-1}$ DL and NDL	Q_{con} PT H_{con} PT H_{ecc} PT H_{con}:Q_{con} ratio H_{ecc}:Q_{con} ratio	↓ H_{ecc} PT (DL 22%; NDL 9%) ↓ H_{ecc}:Q_{con} ratio (DL 14%; NDL 8%)

Cohen et al. (2014)	Semi-pro soccer players N = 9	Male 25y	LIST overground simulation (Nicholas et al., 2000) Isokinetic dynamometer Angular velocity: 120° ·s^{-1} DL	Q_{con} PT H_{con} PT H_{ecc} PT H_{ecc}:Q_{con} ratio Q_{con} angle of PT H_{con} angle of PT	↓ H_{ecc} PT (18%) ↓ H_{ecc}:Q_{con} ratio (12%) ↑ H_{ecc} angle of PT (12%)

DL dominant limb; NDL non-dominant limb

2.8 Re-warm up to offset negative effects of soccer match-play

Referring to section 2.4, where it was highlighted that biomechanical and muscle strength related markers of ACL injury risk are of particular interest because they can be modified, it is appropriate to provide a brief overview of evidence that supports the notion that negative effects of soccer match-play could be offset by intervention. Ultimately, this doctoral study was designed to inform injury prevention programmes and include the investigation of one example of an acute intervention. Here a brief overview will be provided of how re-warmup has been shown to generate positive effects on physical performance, giving scope also for injury prevention through this intervention.

In soccer, a reduction of players' work rate has been observed in the 15 min immediately after the half time interval compared with the first 15 min of match-play (Bradley et al., 2009; Mohr et al., 2003). Studies have suggested that this may be attributed to the drop in muscle temperature that occurs during the typically inactive (passive) half-time period (Lovell et al., 2013; Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004). These findings indicate that consideration should be given to an active re-warm up strategy to attenuate the negative effects of a passive half-time interval.

A short re-warm up intervention (7 min of low/moderate running exercises at 70% of heart rate maximum) during half-time has been shown to maintain elevated muscle temperature and preserve sprint and jump performance over the half-time period (Lovell et al., 2013; Mohr et al., 2004) as well as greater ball possession during match-play (Edholm, Krustrup, & Randers, 2014), indicating a game advantage during the early stages of second half. In addition, re-warm up utilising a high intensity 3 min small sided game has been shown to enhance a subsequent soccer-skill (passing) test, while a 5 repetition of maximum leg press exercise regime improves repeated sprint ability and relative maximum rate of force during counter movement jumps (Zois, Bishop, Fairweather, Ball, & Aughey, 2013). These findings suggest that an active re-warm up would complement the benefits associated with activity before the second half and potentially reduce the increased risk of injury observed during the early stages of the second half (Rahnama, Reilly, & Lees, 2002). Although re-warmup appears to induce positive effects in physical performance, there is to our knowledge a lack of evidence supporting the benefits of such intervention on markers of ACL injury risk, specifically during soccer match-play.

2.9 Conclusions

Non-contact ACL injuries are a serious concern in soccer, with a high percentage of ACL injuries in soccer occurring at the latter stages of match-play. This suggests that exertion induced by soccer match-play may be a potential predisposing factor of ACL injury. Research has provided evidence that fatigue or high levels of exertion may be associated with an increased risk in biomechanical and muscle strength imbalance related markers of ACL injury. The match simulations used in those studies may not represent a similar pattern of exertion as the one that occurs during soccer match-play. There have been various soccer match-play simulations developed using treadmill and overground protocols to simulate soccer matches. Treadmill based simulations have several limitations, including that they only involve straight-line running and not incorporate utility movements. As a result, it could be considered that treadmill protocols developed to date do not adequately simulate the physical demands and activity profile found during actual soccer matches. Alternatively, overground protocols may offer greater ecological validity with the incorporation of utility movements. At present, whether any treadmill or overground simulations can adequately recreate multidirectional soccer match-play remains highly questionable. Furthermore, there are no studies that have investigated the effect of treadmill versus overground soccer specific simulation with velocity, distance and activity profile matched. Therefore, it is necessary to characterize the changes in lower extremity mechanics and muscle strength imbalance caused by each type of simulation. Especially in males the knowledge on the effect of soccer match-play simulation on lower extremity mechanics during dynamic tasks is still lacking. In addition, whether the 15 min half-time rest interval in soccer matches allows to sufficiently restore normal knee mechanics and/or muscle strength imbalances to pre-fatigue levels has not been investigated. This knowledge would be useful for the design of a half-time recovery strategy to minimize the potential for fatigue-related injury.

Based on our observations in the current literature, the investigations presented in this thesis will aim at comparing treadmill versus overground soccer match-play simulations with matched velocity, observing how these affect biomechanical and muscle strength imbalance related markers of ACL injury risk in recreationally trained male and female soccer players. The information obtained will then be used to assess an acute half-time injury prevention strategy, aiming to reduce the risk of ACL injury during the second half of match-play.

Chapter 3

Development of Simulated Soccer Match-Play

3.1 Abstract

Six healthy recreationally soccer trained male subjects (age, 24 ± 2 years; height, 173 ± 7 cm; body mass 76 ± 6 kg) participated in this repeated measures design study. During the testing session, each subject completed a 45 min treadmill and overground simulated match-play involving the same average running velocity and activity profile. Heart rate and RPE were recorded every 5 min throughout the simulation. The physiological responses in the overground simulation (heart rate 169 ± 9 beats.min-1; RPE 14 ± 1) were significantly greater than the treadmill simulation (heart rate 145 ± 12 beats.min-1; RPE 12 ± 1). The heart rate and RPE response in the overground simulation was consistent with soccer players during actual match-play. The treadmill simulation, however, demonstrated a lesser physiological response compared to that as observed during match-play likely due to the exclusion of utility movements and high accelerations and deceleration.

3.2 Introduction

Soccer is characterised by an intermittent and irregular pattern of play (Thomas & Reilly, 1976). As reviewed in Chapter 2, there have been various attempts to replicate the demands of soccer match-play, simulating the irregular pattern of locomotion based on motion analysis of actual soccer match-play. Several soccer-specific treadmill (Drust et al., 2000; Greig et al., 2006) and overground (Lovell et al., 2008; Nicholas et al., 2000; Thatcher & Batterham, 2004) based simulations were used to assess physiological and mechanical responses to such intermittent exercise. These simulations attempt to re-create the activity pattern observed in real matches but with the benefit of being able to control distance covered and velocity patterns closely and being able to undertake experimental assessments of the player's response in a lab-based environment.

The overground soccer-specific aerobic field test (SAFT^{90}), recently developed by Lovell et al. (2008) is arguably the most ecologically valid match-play simulation, including multidirectional and agility movements, and frequent acceleration and deceleration as is inherent to match play. This likely represents the musculoskeletal loads experienced during match-play better than the other types of simulation, making it suitable for assessing the effect of match-play on muscular and biomechanical markers of lower limb injury risk. More so, the SAFT^{90} simulation requires only minor modification to include manoeuvres that, when observed during the simulation, could reveal the generation of high loads, for example a side cutting manoeuvre that has been associated to ACL injury risk.

Before implementing the SAFT^{90} simulation in our work, two concerns remained. First, the work in which the SAFT^{90} match-play simulation has been reported has provided limited detail on the exact physiological responses to the protocol. Second, the protocol was developed to be run over a 20 m distance, which exceeds the dimensions of most biomechanics laboratories, including the one at Liverpool John Moores University, UK. Whilst initially our observations would only be done before and after the match-play simulation, the simulation was to eventually allow researchers to observe side cutting manoeuvres during match-play simulation. Therefore, the main aim of this pilot study was to modify the SAFT^{90} protocol for a 15 m maximal running distance, and to in the first place investigate whether the modified protocol replicated the physiological effects of match-play. We also compared this with a running velocity matched treadmill based simulation to evaluate the effect of added multi-directional movements in the overground simulation. Based on the multi-directional and higher acceleration and deceleration movements in the overground simulation, we hypothesized that the overground simulation would result in a physiological response that is similar to that reported for actual match-play, and that this would be a greater physiological response compared to the treadmill-based version of the simulation.

3.3 Methods

3.3.1 Participants

Six healthy male recreational soccer players volunteered to participate in the study. Participants reported to train 1 to 2 days per week, for 1 to 2 hours per training session. The mean (± SD) age, height, body mass were 24 ± 2 years, 174 ± 6 cm and 74 ± 8 kg, respectively. Participants were questioned on their injury history and none had a recent (< 6 month) knee or thigh injury. Written consent was obtained from all the participants and the study was performed in accordance with the university ethics committee guidelines.

3.3.2 Experimental design

A repeated measures study design was used to determine the physiological responses of the treadmill and overground simulated soccer match-play. Participants were required to attend 3 (one familiarisation and two testing) sessions separated by 4 to 8 days. During the testing session, each participant first completed a 10 min warm up (consisting of light jogging and dynamic movements). Then, participants were randomly assigned (counter-balanced order) to complete either a 45 min overground or treadmill simulation. During both simulations, participants' heart rate and RPE were monitored. Each participant performed all testing periods at the same time of day to account for the effects of circadian variation (Reilly & Brooks, 1986). Participants attended the laboratory in a 3 hours post-absorptive state, having performed no vigorous exercise or consumed any alcohol or caffeine in the 24 hours prior to testing.

3.3.3 Soccer match simulations

The overground match simulation was based on SAFT^{90} as devised by Small et al. (2010). This simulation had been previously validated by Lovell et al. (2008) to replicate soccer match-play, include multidirectional utility movements, and frequent accelerations and decelerations. The course distance was modified from 20 m to 15 m. Compared to the original SAFT^{90} simulation, participants were required to perform additional course lengths to ensure they completed a similar total distance of approximately 5.39 km in 45 min (Small et al., 2010). The overground simulation had four vertical poles incorporated for the participants to navigate through or around using various utility movements (Figure 2).

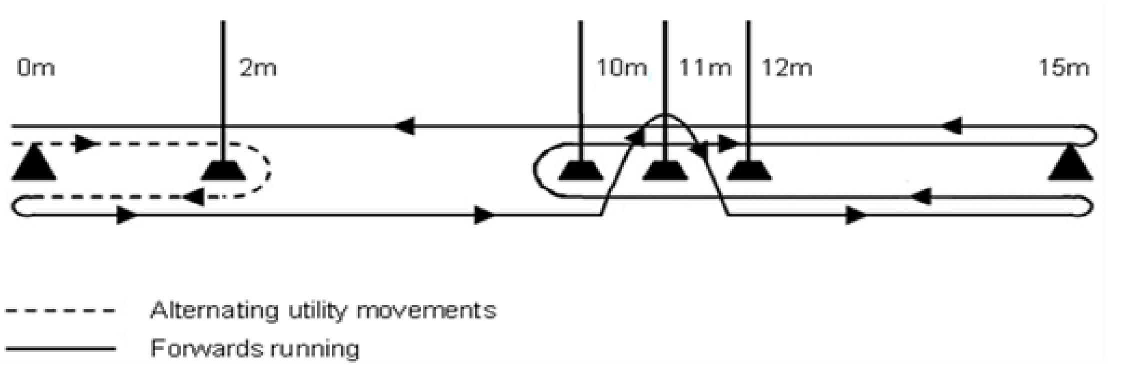

Figure 2. A schematic diagram of the overground match simulation. The simulation was performed with the participants performing either backwards running or side stepping around the first field pole (dashed line), followed by forwards running through the course, navigating the middle three field poles.

The movement intensity and activities (standing, walking, jogging, striding and sprinting) performed by the participants whilst completing the overground course was maintained using verbal cues on an audio recording. A 15 min intermittent activity profile (Figure 3) was developed and repeated three times during the 45 min simulated soccer match-play. No contact actions such as kicking or tackling were performed.

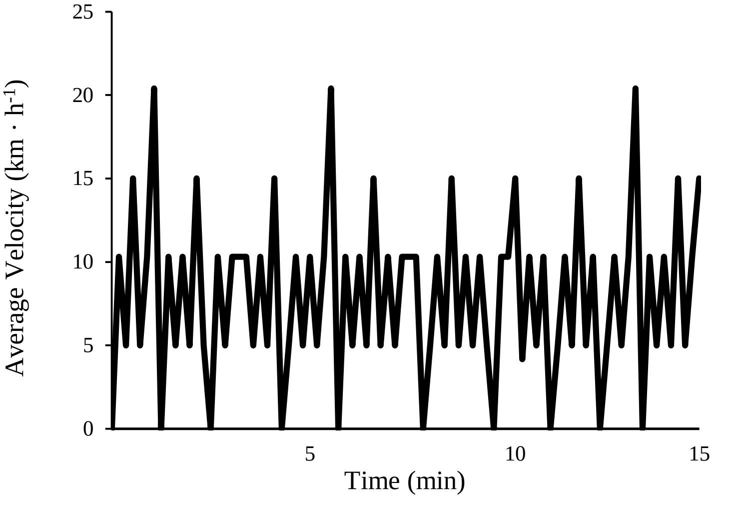

Figure 3. Illustration of the 15 min velocity profile of the modified overground simulation which was repeated three times to recreate locomotion of 45 min soccer match-play.

A treadmill simulation was then designed to elicit a similar average running velocity and activity profile as the overground simulation, yet it was conducted on a motorised treadmill (LOKO S55, Woodway GmbH, Steinackerstraße, Germany). The treadmill simulation imposed relatively slow changes in velocity, accelerating and decelerating the treadmill at 0.50 m · s^{-2}, which is lower than what would typically be observed during the overground protocol. The 15 min activity profile for the treadmill simulation resulted in a distance covered of 1.98 km, giving a 45 min total distance covered of 5.96 km. Whilst having the same velocity profile, lower accelerations and decelerations during the treadmill simulation resulted in a slightly higher total distance than the 5.39 km in the overground simulation. Table 7 shows the average duration spent on one single bout per activity during match simulation.

Table 7. Average duration spent on one single bout per activity during match simulation.

Activity	**Time (s)**
Standing (0.0 km · h^{-1})	4
Walking (5.0 km · h^{-1})	17
Jogging (10.3 km · h^{-1})	10.4
Striding (15.0 km · h^{-1})	7.5
Sprinting ($\geq$ 20.4 km · h^{-1})	2.45

3.3.4 Heart rate and RPE

Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored every five min throughout the simulation.

3.2.5 Statistical Analyses

Statistical analysis was carried out using statistical software package SPSS (Version 20; SPSS Inc., USA). Mean and standard deviation were calculated for each dependent variable. A two-way analysis of variance (ANOVA) was performed to compare differences in heart rate and RPE over time (0, 45, 60 min) and between conditions (overground vs treadmill). The alpha level was set at 0.05.

3.4 Results

3.4.1 Heart rate

The mean heart rates during exercise (time 5 min to 45 min) for the treadmill and overground simulations were 145 ± 13 and 168 ± 8 beats · min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{1.7,8.9}$ = 5.96, P = 0.025). While heart rates increased over time relative to baseline within each simulation ($F_{2.8,13.9}$ = 229.5, P < 0.001), the heart rates increased significantly more for the overground simulation compared to the treadmill simulation ($F_{1,5}$ = 68.9, P < 0.001; Figure 4 a).

3.4.2 Rate of perceive exertion

The mean RPE during exercise (time 5 min to 45 min) was 12 ± 1 and 14 ± 2 for the treadmill and overground simulations respectively, showing a trend towards significant interaction between simulation and time ($F_{2,10}$ = 3.52, P = 0.069). While RPE increased over time relative to baseline within each simulation ($F_{1.6,8.2}$ = 47.8, P < 0.001), the RPE increased significantly more for the overground simulation relative to the treadmill simulation ($F_{1,5}$ = 13.0, P = 0.015; Figure 4 b).

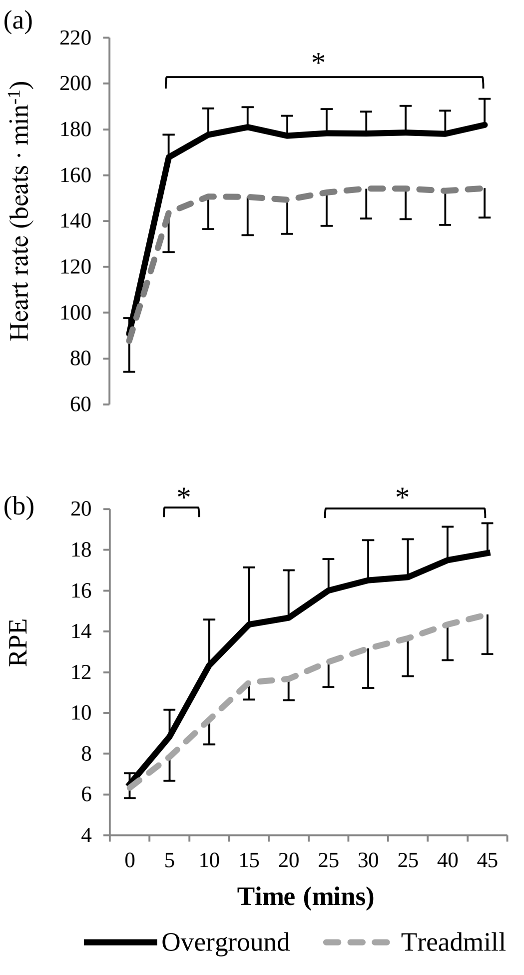

Figure 4. Heart rate (a) and RPE (b) changes over time during treadmill and overground simulations. * Indicates a significant difference between simulations.

3.5 Discussion

The primary findings of this pilot study were that the modified overground match simulation induced a similar physiological response as in SAFT^{90} (Lovell et al., 2008; Lovell et al., 2013) and during actual match-play (Bangsbo et al., 1991; Mohr et al., 2003; Thatcher & Batterham, 2004; Van Gool, Van Gervan, & Boutmans, 1998). We also found that, despite average running velocity being matched, we observed a significantly greater increment of heart rate and RPE in the overground simulation compared to the treadmill simulation.

3.5.1 Effects of soccer match simulations on heart rate

The magnitude of the heart rate response tended to increase as a function of exercise duration, suggesting a cumulative effect of physiological strain. The mean heart rate response in the overground simulation was 169 ± 8.8 beats · min^{-1}. A soccer player's average heart rate during match play has been shown to range from 156 to 167 beats.min^{-1} depending on the level of the players (Bangsbo et al., 1991; Mohr et al., 2003; Thatcher & Batterham, 2004; Van Gool et al., 1998). These heart rate responses are all very similar to the $SAFT^{90}$ simulation (Lovell et al., 2008; Lovell et al., 2013), which was reported as 162 ± 6.0 beats · min^{-1}. As the present overground simulation course was 5 m shorter compared to the $SAFT^{90}$, it incorporated more acceleration and deceleration movement activity, likely leading to slightly greater physiological stress.

The mean heart rates during the treadmill simulation were considerably lower at 145.4 ± 13.5 beats · min^{-1}. Also a previously published treadmill simulation study reported a mean heart rate value of 125 beats · min^{-1} (Greig et al., 2006). Those results are below the values recorded during actual soccer match play and those in the present study's overground simulation. In contrast, one study had reported higher heart rate values of 161.0 ± 8.0 beats · min^{-1} in an intermittent treadmill simulation (Drust et al., 2000). This simulation was based on work-rates of professional soccer players as recorded by Thomas and Reilly (1976). Whilst their activity profile incorporated only 46 changes in movement intensity over the 45 min, compared to 84 during the present study, this resulted in substantially longer time spent performing individual movement bouts (walking 35.3 s, jogging 50.3 s, cruising 51.4 s and sprinting 10.5 s). Therefore, a substantially greater amount of time was spent performing the high intensity activities, totalling more than 50% of the total distance covered compared with 16% observed during 45 min of actual matches (Thatcher & Batterham, 2004) and just over 15% during the $SAFT^{90}$ simulation. In addition, their players completed a total distance in excess of ~9 km during the 45 min treadmill protocol which is substantially further than what is covered (5 – 6 km) during typical 45 min match play (Stolen et al., 2005).

3.5.2 Effects of soccer match simulations on RPE

Rate of perceived exertion profiles were in line with heart rate response profiles during both simulations. Similar as with heart rate responses, subjective RPE during the overground simulation (14.1 ± 1.2) was significantly greater than during the treadmill simulation (11.5 ± 0.8). This result is consistent with observations from previous studies using overground (Nicholas et al., 2000) and treadmill (Greig et al., 2006) soccer match simulations.

The lower heart rate and RPE response shown during the treadmill compared to the overground simulation may have been due to a number of factors. Firstly, by using a motorised treadmill this may have reduced the fatiguing effect by automatically administering acceleration and deceleration demands. Research has observed approximately 500 deceleration movements during a football match (Bloomfield, Polman, & O'Donoghue, 2009), which has been postulated to increase the eccentric stress. The lower physiological responses to running on a motorised treadmill may be attributed to the absence of such high number of self-performed accelerations and decelerations. Secondly, the treadmill simulation generates only forward locomotion, ignoring the presence of a broad range of utility movements as part of soccer match-play. Up to 36.9% of total distance covered during soccer matches are performed using utility movement (Thatcher & Batterham, 2004). These movements have been reported to significantly enhance the physiological load, metabolic cost and muscular fatigue in soccer (Bangsbo, 1994a).

3.6 Conclusions

The newly developed modified overground simulation resulted in heart rate and RPE responses that were consistent with those found during actual match-play. The overground simulation imposed significantly higher heart rate and RPE response than treadmill simulation at the same average running velocity and activity profile. Therefore, this pilot study has demonstrated that the exertion during the overground simulation is a better approximation to that of actual match-play than during the treadmill simulation, supporting the added value of incorporating accelerations and decelerations as well as utility movements that are inherent to actual match-play. Modifying the SAFT^{90} simulation to 15 m distance appeared to have a small effect on the heart rate and perceived responses to the simulation, supporting the use of the modified overground protocol as an ecologically valid soccer match-play simulation.

Chapter 4

Effects of Treadmill versus Overground Soccer Match Simulations on Biomechanical Markers of Anterior Cruciate Ligament Injury Risk in Side Cutting

4.1 Abstract

Nineteen male recreational soccer players completed a 45 min treadmill and overground match simulation. Heart rate and RPE were recorded every 5 min. Prior to exercise (time 0 min), at 'half-time' (time 45 min) and 15 min post exercise (time 60 min) participants performed five trials of 45° anticipated side cutting manoeuvres. Knee abduction moments and knee extension angles were analysed using two-way repeated measures ANOVA ($\alpha = 0.05$). Physiological responses were significantly greater during the overground (HR 160 ± 7 beats · min-1; RPE 15 ± 2) than treadmill simulation (HR 142 ± 5 beats · min-1; RPE 12 ± 2). Knee extension angles were significantly increased over time and were more extended at time 60 min compared to time 0 min and time 45 min. No significant differences in knee abduction moments were observed. Although knee abduction moments were not altered over time during both simulations, passive rest during half-time induced changes in knee extension angles that may have implications for ACL injury risk.

4.2 Introduction

Anterior cruciate ligament (ACL) injuries have a high prevalence in soccer with incidence rates of between 0.6 and 8.5% in male players, regardless of their playing level (Walden, Hagglund, Werner, et al., 2011). The majority of ACL injuries take place during non-contact utility movements such as running, jumping, landing, or suddenly changing direction (e.g. side cutting) (Fauno & Wulff Jakobsen, 2006; Hawkins et al., 2001). The side cutting manoeuvre requires a sudden deceleration upon impact with the ground, accompanied by a rapid change in direction (McLean, Lipfert, et al., 2004). Studies have shown that during the weight acceptance phase of side cutting, which is from the initial foot contact to the first trough in the vertical ground reaction force (Dempsey et al., 2007), peak abduction knee moments are up to two times higher than those observed during straight line running indicating that this may be the period of high ACL strain (Besier, Lloyd, Cochrane, et al., 2001). When the peak abduction moments are coupled with anterior tibial translations, ACL strain is significantly higher (Withrow et al., 2008). An extended knee position at initial contact during side cutting has also been associated with increased ACL strain, and with increased anterior tibial shear force due to an increased patellar tendon-tibia shaft angle (Hughes & Watkins, 2006; Laughlin et al., 2011; Yu et al., 2006).

In soccer, the rate of injuries increase with match duration (Ekstrand et al., 2011; Hawkins et al., 2001). Furthermore, consistent with an increased injury rate with match duration are observed decreases in distance covered and high intensity running (Bangsbo et al., 1991; Mohr et al., 2003). Together, these findings lead to a speculation that exertion induced by match duration may alter movement mechanics (Greig, 2009; Sanna & O'Connor, 2008; Small, McNaughton, Greig, Lohkamp, et al., 2009).

Numerous studies have reported that high levels of exertion induced by a short duration high intensity exercise can alter lower extremity mechanics during side cutting manoeuvres. Tsai et al. (2009) observed an increase in the peak knee abduction moments (peak external knee abduction moments) as well as peak knee internal rotation angles in anticipated side cutting after high intensity consecutive repetitions of vertical jumps and short sprints. In addition, Lucci et al. (2011) reported an increased knee extension angle at initial contact and decreased knee internal rotation in unanticipated side cutting after short duration and high intensity exercises consisting of a series of step-up and down movements, vertical jumps, and agility drills. However, the high intensity and short duration exercises used in both studies do not represent the level of exertion and activity profile as occurs during a soccer match.

The studies by Greig (2009) and, Sanna and O'Connor (2008) are perhaps the closest attempts to investigate the effect of soccer match exertion on knee joint mechanics. Greig (2009) conducted 90 min soccer match simulations with a motorised treadmill and observed a more extended knee at initial contact after 45 and 90 min, and after the half-time interval. The treadmill match simulation was designed to represent the mechanical demands of the intermittent running characteristics of soccer, replicating the short duration of exercise bouts, and subsequently providing a valid frequency of speed changes (Greig, 2009). Furthermore, Sanna and O'Connor (2008) used a 60 min overground soccer match simulation and found that this elicited significant pre to post differences in knee internal rotation angles but no changes in peak knee abduction moments and knee extension angles during anticipated side-cutting. Their overground simulation consisted of straight-line shuttle runs at various speeds between two cones positioned 20 m apart. The disparity in protocols may be a reason for the dissimilar findings between these studies. Although both simulations have represented either the mechanical (Greig, 2009) or physiological (Sanna & O'Connor, 2008) demands of soccer match-play, neither incorporated multidirectional utility movements. As has been observed in Chapter 3, overground simulation may offer better external validity for actual match-play and for the investigation of knee injury biomechanics. At present, whether any treadmill or overground simulations can accurately recreate soccer match-play and influence mechanical loading remains unknown.

The primary objective of this study was to compare the effects of match exertion induced by treadmill and overground soccer match simulations on knee mechanics during side cutting. The null hypothesis was that there would be no differences in peak knee abduction moments at weight acceptance phase and knee extension angles at initial contact during side cutting between the treadmill and overground match simulations.

4.3 Methods

4.2.1 Participants

Twenty healthy male recreational soccer players volunteered to participate in the study. An a priori power calculation was conducted to estimate the sample needed to establish differences between simulations. Based on previous studies (Borotikar et al., 2008; Chappell et al., 2005; McLean & Samorezov, 2009) focusing on the effects of fatigue on lower limb mechanics, it was estimated that a minimum sample size of approximately 15 participants was needed to achieve 80% statistical power, and with an alpha level of 0.05. Participants trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, body mass were 26 ± 5 years, 1.74 ± 0.07 m, 73 ± 7.8 kg, respectively. Participants were questioned on their injury history and none had previous ACL injury and all had been free from any other knee or thigh injury within the previous 6 months that could interfere with their performance of utility skills. Written consent was obtained from all the participants and the study was performed in accordance with the university ethics committee guidelines.

4.2.2 Experimental design

In a single group repeated measures design, participants were required to attend the laboratory for 3 separate sessions (one familiarisation and two testing). Participants attended the laboratory having been requested to perform no vigorous exercise or consume any alcohol or caffeine in the 24 hours prior to testing. During the familiarisation session, participants were familiarised with the cutting manoeuvre and the treadmill and overground match simulations for 10 min each. During the first testing session, and after completing a 15 min dynamic warm-up, participants were randomly assigned to perform either the treadmill or overground 45 min match simulation first. Before exercise (time 0 min), immediately at 'half-time' (time 45 min) and after 15 min 'half-time' rest (time 60 min) participants performed five 45° side cutting manoeuvres regardless of the match simulation completed. During the 15 min 'half-time' period participants remained seated and were allowed to drink water. Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored continuously every five min. The second testing session was undertaken 4 to 8 days after the first testing session, was conducted at the same time of the day, and participants completed the other 45 min match-play simulation.

4.2.3 Soccer match simulations

The overground and treadmill match simulation was similar to that devised by Small et al. (2010), and previously explained in Chapter 3. A 45 min duration simulation was used instead of a 90 min duration because lower limb strength (Greig, 2008; Robineau et al., 2012; Small et al., 2010) and knee mechanical (Greig, 2009) changes were primarily observed at half-time with only small further reductions over the second 45 min. Furthermore, high injury incidence in the last 15 min of the first half suggests that 45 min duration may already induce increased injury risk (Hawkins et al., 2001).

4.2.4 Assessment of side cutting kinematics and kinetics

To generate the biomechanical markers of ACL injury risk, three-dimensional marker trajectories were collected by 10 infrared cameras at 250 Hz (Oqus cameras, Qualisys, Gothenburg, Sweden) and forces collected by a 0.9 x 0.6 m force platform (Kistler, Winterhur, Switzerland) embedded in the floor, sampling at 1500 Hz. The same investigator placed 44 reflective markers on all participants (Figure 5). A full-body six-degrees-of-freedom kinematic model (the LJMU Lower Limb Trunk model, Appendix 1) with functional hip and knee joints was applied using Visual3D (C-motion, Germantown, MD, USA) with segmental data based on regression equations and using geometrical volumes to represent each segment (Dempster & Gaughran, 1967). Full details of the model are described elsewhere (Malfait et al., 2014; Vanrenterghem, Gormley, Robinson, & Lees, 2010)

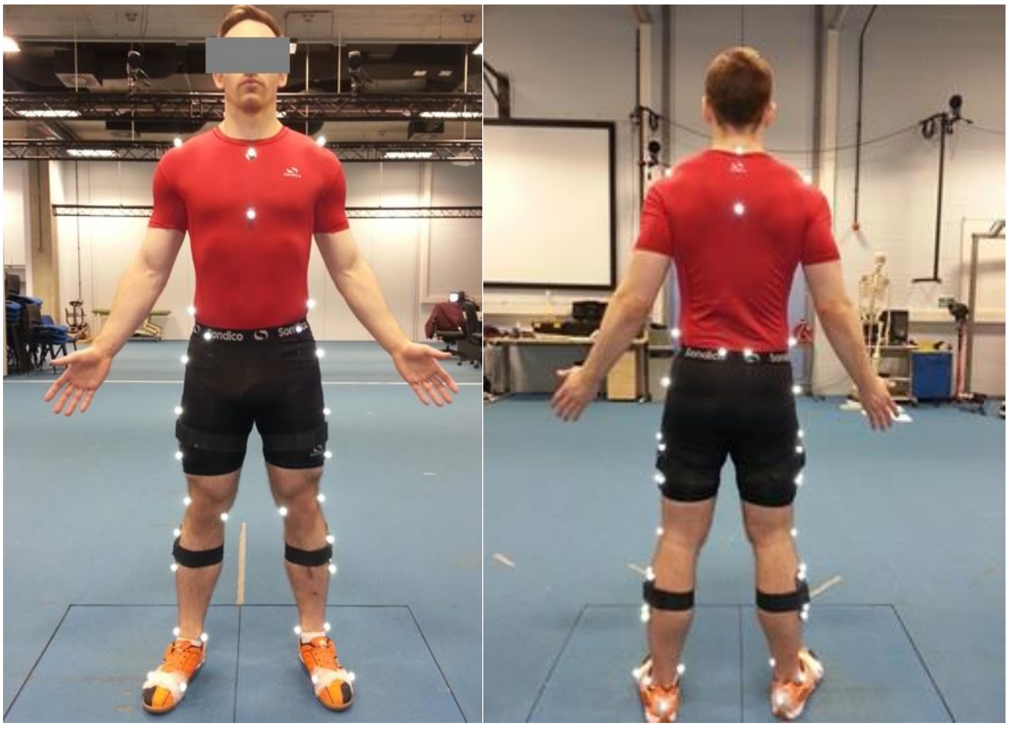

Figure 5. The LJMU Lower Limb Trunk model marker set.

Marker trajectories and force data were filtered using a fourth-order low pass Butterworth filter with a cut off frequency of 20 Hz (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & Van Den Bogert, 2012) prior to inverse dynamics calculations. The cut off frequency of 20 Hz was similar with our previous studies (Malfait et al., 2014; Sankey et al., 2015; Vanrenterghem et al., 2010) and was consider appropriate to measure knee loading during dynamic task. Specifically, the frontal plane knee moment was used to retrieve the peak external knee abduction moments during the weight acceptance phase as defined in Dempsey et al. (2007). For a side cutting manoeuvre, we describe an abduction moment as that exerted by the environment on the knee joint, which is opposed by an equal and opposite adduction moment generated by muscles and ligaments around the knee (Figure 6). It has been shown that maximum magnitude valgus and internal rotation moments were found within the weight acceptance phase (Besier, Lloyd, Cochrane, et al., 2001). Sagittal plane knee joint angles at initial contact were also calculated. The initial contact was defined as the time instant when the foot made contact to the ground, i.e. the instant at which the unfiltered vertical ground reaction force exceeded 20 N, and take off was determined as the time instant when the ground reaction for return to a value lower than 20 N.

Figure 6. The magnitude and direction of the ground reaction force (GRF) are shown by the height and direction, respectively, of the straight arrow. The length of the moment arm (MA) of the GRF acting about the knee joint is indicated by dotted lines. The knee abduction moment increases if the length of the MA increases, or the GRF magnitude increases, or both.

To ensure an approach speed of 4.0 - 5.0 m · s^{-1} prior to the side cutting manoeuvres (Vanrenterghem, Venables, Pataky, & Robinson, 2012), approach speed was recorded using photocell timing gates (Brower Timing System, Utah, USA) that were placed 2 m apart and 2 m from where the side cut was executed. The side cut involved a sudden anticipated change of direction using the dominant right limb (all participants were right limb dominant) to the left at 45° to the initial approach, whilst landing with the right foot on the force platform (Figure 7). The participants' dominant limb was determined as the limb used to kick a ball. Males have been found to be more likely to injure the ACL in their kicking limb (Brophy, Silvers, Gonzales, & Mandelbaum, 2010). The 45° cutting angle was marked on the platform with tape to provide a visual indication of the required exit direction from the task. Cones were also placed 3 m from the force plates to mark a target gate at the required 45°. To limit inter-trial variability, a successful trial was only valid if approach speed was within the required range, and the stance foot landed entirely on the force plate.

Figure 7. Participant performing 45° anticipated side cutting.

4.2.5 Statistical analyses

Paired t-tests were used to compare pre-exertion (time 0 min) conditions (overground vs. treadmill). This was conducted to assess baseline assumption (pre-exertion was equal between simulations). Subsequently, a 2 (simulation: treadmill, overground) × 3 (time: 0 min, 45 min, 60 min) repeated measures analysis of variance (ANOVA) was conducted for each dependent variable using the statistical software package SPSS (Version 20; SPSS Inc., USA). Mauchly's test of sphericity was used to check for equality of variance between simulations and different times. If the Greenhouse − Geisser epsilon was >0.75 the Huynh Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction value was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis. Match simulations and time were treated as independent variables. The dependent variables used in this study included peak knee abduction moment at weight acceptance phase and knee extension angles at initial contact. Each of the five trials was averaged. The alpha level was set at 0.05.

4.4 Results

One participant was unable to complete the full protocol. All data reported are for the remaining nineteen participants.

4.3.1 Physiological parameters

The mean heart rates during exercise (time 5 min to 45 min) for the treadmill and overground simulations were 142 ± 5 and 160 ± 7 beats · min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{3.2,57.8} = 10.2$, $P < 0.001$; Figure 8 a). While heart rates increased over time within each simulation ($P < 0.001$), the heart rates increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$). Similarly, the mean RPE during exercise (time 5 min to 45 min) was 12 ± 2 and 15 ± 2 for the treadmill and overground simulations respectively, with a significant interaction between simulation and time ($F_{3.5,63.5} = 14.8$, $P < 0.001$; Figure 8 b). While RPE increased over time within each simulation ($P < 0.001$), the RPE increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$).

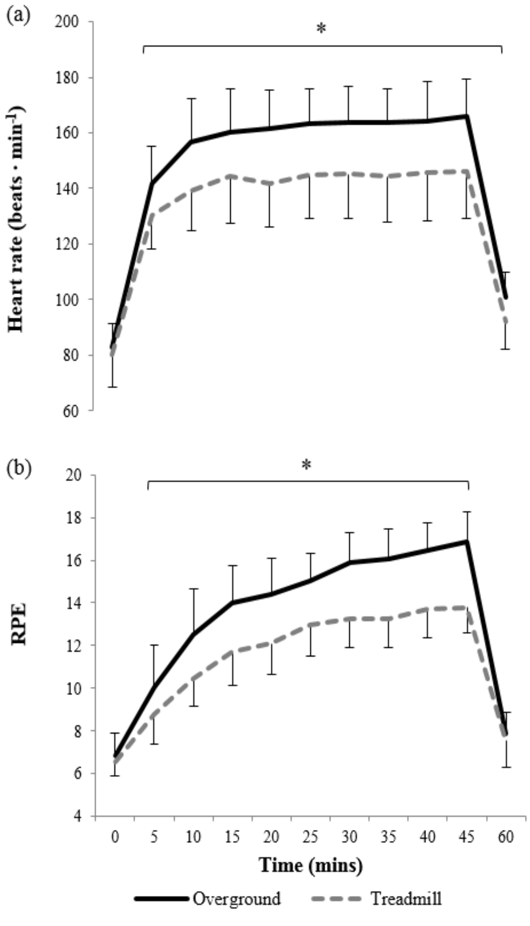

Figure 8. Heart rate (a) and RPE (b) changes over time during treadmill and overground simulations. * Indicates a significant difference between simulations.

4.3.2 Effects of soccer match simulations on biomechanical markers of ACL injury

In the peak knee abduction moments, there was no significant interaction between simulation and time ($F_{2,36}$ = 0.49, P = 0.619). Similarly, no significant differences between simulations ($F_{1,18}$ = 3.82, P = 0.066) or over time ($F_{2, 36}$ = 2.96, P = 0.064; Figure 9 a, 10 a and 11 a) were observed.

There was no significant interaction between simulation and time ($F_{2,36}$ = 2.61, P = 0.087), or any significant differences observed in knee extension angles at initial contact between simulations ($F_{1,18}$ = 0.78, P = 0.388). However, a significant change was observed over time ($F_{1.2,22.8}$ = 4.94, P = 0.029; Figure 9 b, 10 b and 11 b). Pairwise comparisons revealed that knee extension angles increased (became more extended) at time 60 min compared to time 0 min (P = 0.027), and time 60 min compared to time 45 min (P = 0.009).

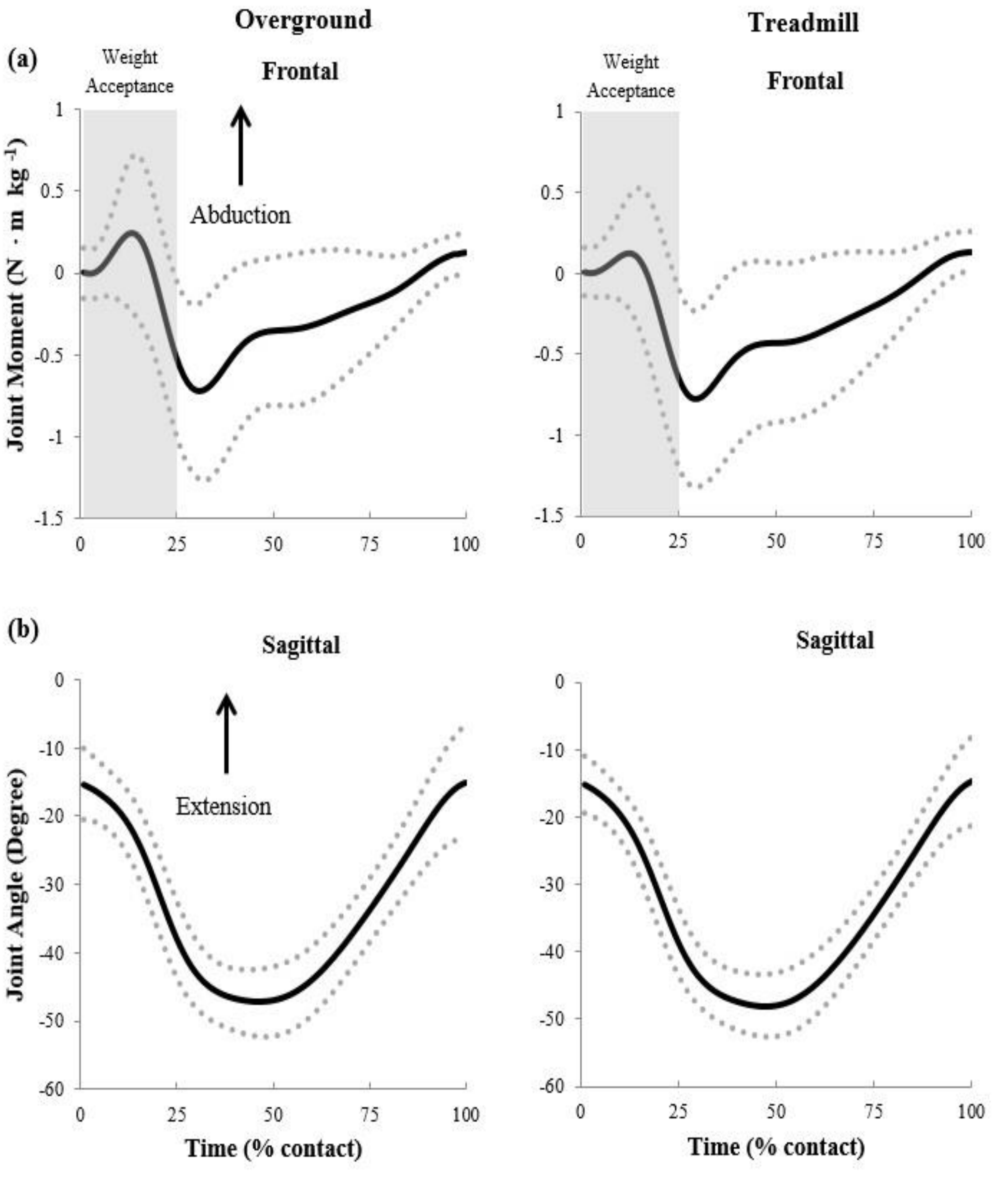

Figure 9. Example of pre match simulation (time 0 min) average time series (solid line) with standard deviation (dotted line) of knee abduction moments with weight acceptance phase indicated (a) and knee extension angles (b) during overground and treadmill simulations.

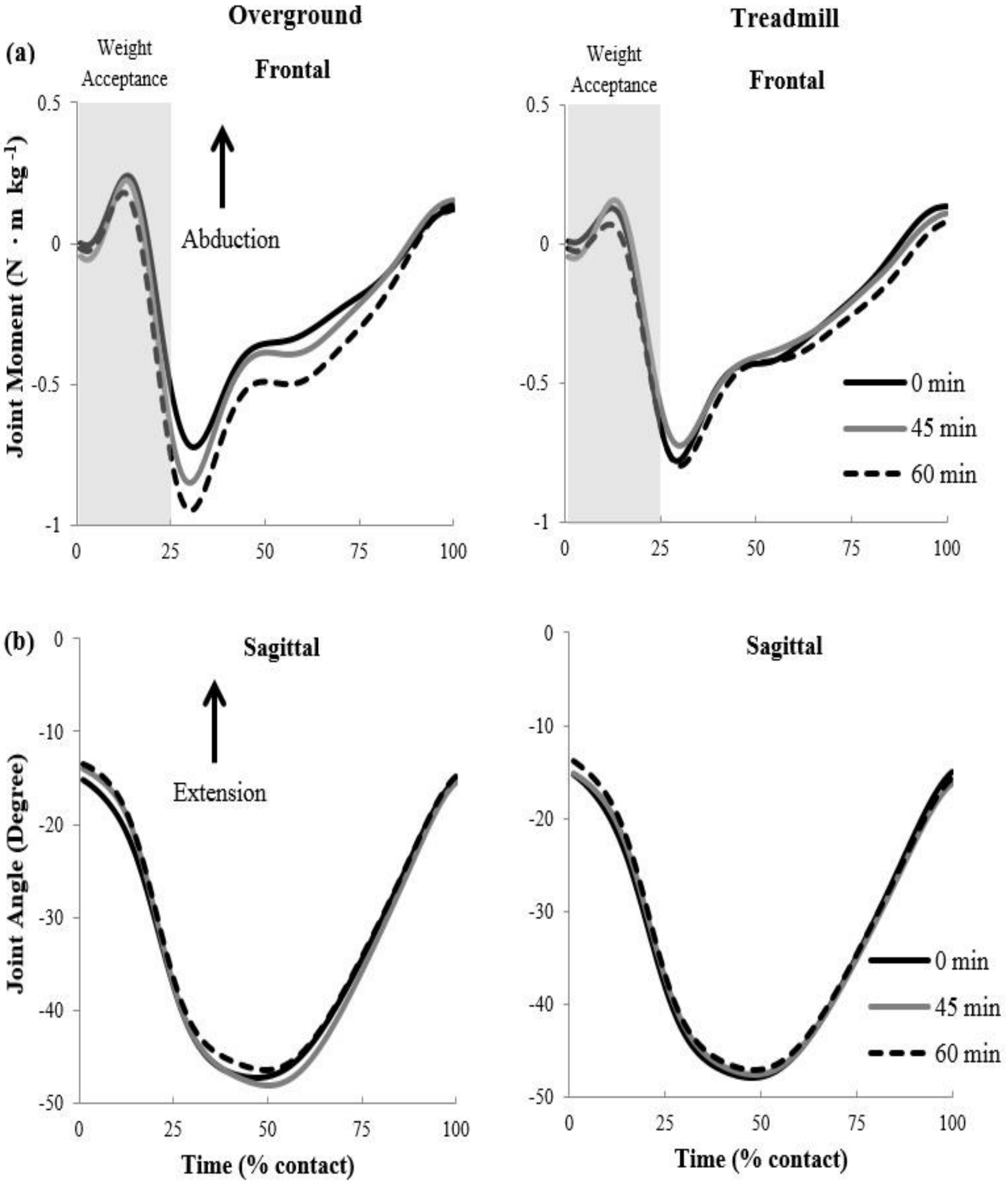

Figure 10. Knee abduction moments at weight acceptance phase (a) and knee extension angles at initial contact (b) during treadmill and overground simulation.

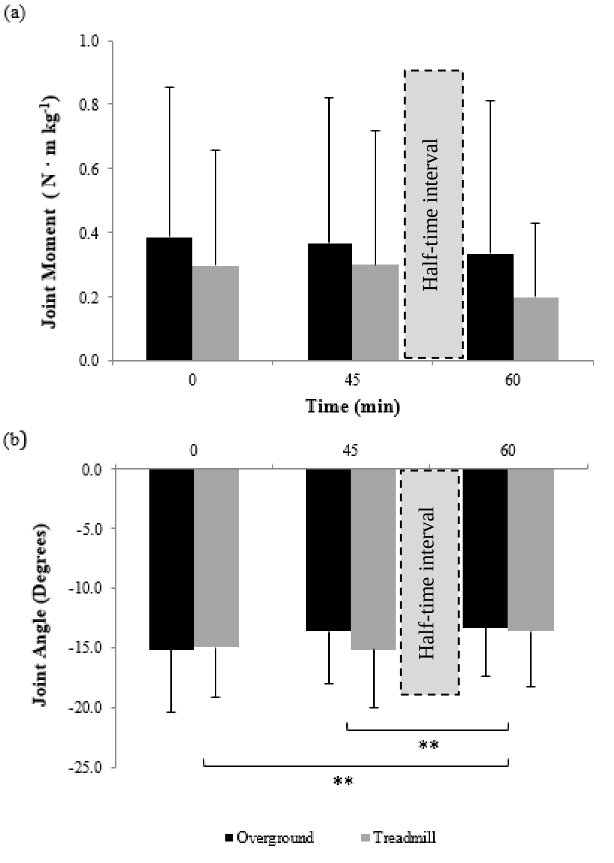

Figure 11. Peak knee abduction moments (a) and knee extension angles (b) during treadmill and overground simulation. **Indicates significant difference over time.

4.4 Discussion

The main findings of the present study indicate that two different types of soccer match simulations, matched for average running velocity, elicited significant differences in heart rate and RPE values, with the overground simulation inducing a greater physiological response. Although similar outcomes were observed when comparing peak knee abduction moments, significant increases in knee extension angles were observed in both simulations at time 60 min, after 15 min of rest. More extended knee joint angles at initial contact have been theorised to increase the likelihood of ACL injury, which will be addressed below.

4.4.1 Effects of soccer match simulations on physiological parameters

Our results show that the overground match-play simulation induced a greater physiological response compared to the treadmill simulation, supporting previous findings on Chapter 3. The mean heart rate response in the overground simulation (160 ± 7 beats · min^{-1}) was consistent with values reported in Chapter 3 and during actual match-play (Bangsbo, 1994a; Krustrup et al., 2006; Mohr et al., 2004; Thatcher & Batterham, 2004; Van Gool et al., 1998) . However, the mean heart rate in the treadmill simulation (142 ± 5 beats · min^{-1}) was substantially lower, even if they were still higher than 125 beats · min^{-1} as reported in a treadmill match simulation study (Greig et al., 2006) . It is likely that the heart rate values in our study were higher as our participants were recreationally active as opposed to semi-professional players. An increased heart rate response was supported by the increased RPE during both simulations. Our RPE values were consistent with Chapter 3 and previous studies using overground (Nicholas et al., 2000) and treadmill (Greig et al., 2006) simulations. As overall running velocity was matched between simulations, we attribute the lower heart rate and RPE response shown during the treadmill simulation to the absence of high acceleration-deceleration and multidirectional utility movements. The close similarities between physiological responses observed during the present study and values reported from actual match-play justify the use of overground simulations for replicating the demands of soccer, more so than treadmill simulations.

4.4.2 Effects of soccer match simulations on peak knee abduction moments

Our results indicated that both the treadmill and overground simulation showed no differences in peak knee abduction moments. This finding is consistent with Sanna and O'Connor (2008) whilst in other studies an increase in peak knee abduction moments has been reported (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009). This discrepancy can be explained through differences in task and type of simulation used.

Firstly, anticipated side cutting is a relatively simple task and does not require maximum amount of force. Participants may have retained sufficient ability to complete the manoeuvre without excessive loading the knee joint. The demands of unanticipated side cutting have been shown to induce greater differences in electromyographic responses (Besier, Lloyd, Cochrane, et al., 2001) and knee mechanics after fatigue (Borotikar et al., 2008) compared to the anticipated side cutting manoeuvre. Secondly, those studies which observed increased peak knee abduction moments utilised jump tasks and/or high intensity, short duration (< 10 min) exercises designed to induce a level of volitional exhaustion. In our study, a 45 min soccer match simulation was believed to be more representative of the demands associated with actual match-play.

4.4.3 Effects of soccer match simulations on knee extension angle at initial contact

Our study observed significant effects on the knee extension angle at initial contact after 15 min of passive rest in both simulations. A similar treadmill-based match-play simulation has also induced a more extended knee at initial contact (Greig, 2009), although care should be taken in this comparison as their task involved a 180° cut rather than a 45° side cutting manoeuvre. Both are functional soccer movements yet they induce different mechanical challenges, with our task being a running change of direction rather than a complete stop-start movement. This difference likely explains that in our study the knee was much more extended (approximately 13° versus 30°), and the effect of the match-play simulation was less (2° versus 9°). The passive half-time interval did not restore knee joint angles to pre-simulation values, and the knee was more extended after half-time than at the start of the half-time interval. A more extended knee can lead to higher strain of the ACL in combined loading situations (Markolf et al., 1995) and expose the knee to excessive anterior shear force mechanisms (Hashemi et al., 2011). As been previously mentioned in the previous chapter, the increased risks of ACL injury from a more extended knee during landing could be explained by combined changes in ACL elevation angle, the patellar tendon insertion angle and the angle of insertion of the hamstrings (Blackburn & Padua, 2008). With the knee more extended during landing, the elevation angle of the ACL with respect to the tibial plateau increases. Under this configuration, the anterior tibial shear force generated by the quadriceps/patellar tendon is increasing, resulting in a greater ACL loading. Furthermore, as the knee is more erect during landing, the patellar tendon insertion angle with respect to the tibial longitudinal axis increases (Zheng et al., 1998) and increases the anteriorly directed component of the quadriceps force (Nunley et al., 2003; Yu & Garrett, 2007), increasing the load placed on the ACL. With more extended knee during landing, the angle of insertion of the hamstrings with respect to the tibial longitudinal axis decreases. Thus, limiting the hamstrings' potential to counteract anterior tibial force to the ACL (Pandy & Shelburne, 1997). In fact, a certain abduction moment at the knee is expected to cause more strain on the ACL ligament when the knee is in a more extended position (Markolf et al., 1995). Other studies investigating performance following half-time have similarly observed impaired sprint (Mohr et al., 2004) and sprint kinematic performance (Small, McNaughton, Greig, Lohkamp, et al., 2009), which the authors attributed to lowered body temperature. These findings indicate that consideration should be given to active re-warm up strategies during the half-time interval which, as recently shown, would complement the physiological benefits associated with activity before the second half (Lovell et al., 2013).

4.4.4 Limitations

The present study has revealed that overground simulated match-play is more representative of actual match play than treadmill based simulations. Nevertheless, neither of those simulations included actual ball handling skills or the presence of an opponent, and all observed movements were fully anticipated. Future research might consider the inclusion of unanticipated tasks in the match simulation, as well as the evaluation of biomechanical markers of injury risk during unanticipated tasks. Also, the biomechanical observations made were only and limited to the observation of previously identified markers of injury risk. It may well be possible that further interrogation of the movement kinematics and kinetics would still reveal effects of match simulation, for example through the use of more comprehensive statistical approaches such as Principal Component Analysis or Functional Data Analysis (for a general overview of these methods, see for example Deluzio, Harrison, Coffey, and Caldwell (2004). Whilst such analyses could highlight other potentially relevant movement adaptations, the relationship of any such adaptations with injury risk would still remain largely unknown.

4.5 Conclusions

To our knowledge, this was the first study to report changes in heart rate, RPE, and knee joint mechanics directly comparing running velocity matched treadmill and overground soccer match simulations. The overground simulation imposed significantly higher heart rate and RPE response than treadmill simulation, likely due to the inclusion of utility movements and higher accelerations and decelerations. For this reason, the overground simulation is believed to better represent actual match-play demands, and is expected to be more suitable for use in further investigation into the effect of match-play on ACL injury risk. We nevertheless found no different effects between treadmill and overground simulation on biomechanical risk factors of ACL injury in male recreational soccer players. Neither simulation elicited changes in peak knee abduction moments or extension angles. However, knee angles at initial contact tended to be more extended following 15 min half-time interval, which may have implications for ACL injury risk.

Chapter 5

Effects of Treadmill versus Overground Simulated Soccer Match-Play on Muscle Strength Markers Related to Anterior Cruciate Ligament Injury

5.1 Abstract

Fifteen male recreational soccer players completed a 45 min treadmill and overground match simulation. Prior to exercise (time 0 min), at ‘half-time’ (time 45 min) and 15 min post exercise (time 60 min) participants performed five maximal dominant-limb isokinetic contractions for concentric and eccentric hamstrings (H_{con} and H_{ecc}), and concentric quadriceps (Q_{con}). A two-way repeated measures ANOVA was used to identify significant differences between conditions and over time, with α=0.05. In the overground simulated match-play, the hamstring eccentric (H_{ecc}) peak torques significantly reduced 12.5% after time 45 min and reduced further to 14.4% after half-time interval. In contrast, the treadmill simulation failed to produce any significant changes after 45 min though a significant reduction of 5.2% was observed after the passive half-time interval. A significant reduction in the functional hamstring eccentric to quadriceps concentric (H_{ecc}:Q_{con}) ratio of 7.4% was observed between time 0 min to time 45 min and between time 0 min to 60 min by 10.3%. No significant changes were observed in the conventional H_{con}:Q_{con} ratio or the angle of peak torques in all muscle contractions. The higher impairment observed during the overground simulated match-play compared to the treadmill suggest the overground simulation better represent actual match-play demands, and is more suitable for use in further investigation into the effect of match-play on ACL injury risk.

5.2 Introduction

An imbalance between the strength developed by quadriceps and hamstring has been identified as a potential risk factor for ACL injury (Sangnier & Tourny-Chollet, 2008; Soderman et al., 2001). In particular, the functional hamstrings to quadriceps ratio (H_{ecc} : Q_{con}, defined as the ratio of the peak eccentric torque of the hamstrings to the peak concentric torque of the quadriceps) is believed to have an optimum range of 0.70 – 1.0, with studies suggesting that a high H_{ecc} : Q_{con} ratio might protect individuals from ACL injuries (Aagaard et al., 1998; Hewett et al., 2001). In addition, with the hamstring protect the ACL by preventing anterior tibial translation, it has been shown that also the risk of hamstring injuries was increased 17 times when the conventional hamstrings to quadriceps ratio value (H_{con} : Q_{con}, defined as the ratio of the peak concentric torque of the hamstrings to the peak concentric torque of the quadriceps) was below 0.60 (Yeung et al., 2009).

It has been shown that exertion induced by soccer match simulation significantly decreased concentric and eccentric hamstrings (H_{con} and H_{ecc}), and concentric quadriceps (Q_{con}) peak torque, which contribute to a 3 – 10% reduction in the H_{con} : Q_{con} ratio (Rahnama et al., 2003). However, the relevance of using H_{con} : Q_{con} has been questioned, since opposing muscles cannot develop simultaneous concentric contractions (Croisier et al., 2002). A greater reduction in functional H_{ecc} : Q_{con} ratio of 13 – 30% has been observed during match-play in males (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Rahnama et al., 2003; Small et al., 2010). These findings show that the functional H_{ecc} : Q_{con} ratio is more affected during match-play and more representative of muscular demands in soccer (e.g., kicking and sprinting), where the hamstrings are believed to act eccentrically to decelerate the tibia during rapid and powerful knee extensions (Bruckner & Khan, 2012; Sun et al., 2015). These reductions in functional H_{ecc} : Q_{con} ratio are likely attributed to the reductions of eccentric hamstrings contractions compared to the quadriceps. Furthermore, studies have also observed a shift in the angle of peak torque towards longer muscle lengths in Q_{con} and towards shorter muscle lengths in H_{ecc} during soccer match-play (Cohen et al., 2014; Small et al., 2010), which the authors proposed could well be important markers of ACL injury risk.

These studies investigating the effect of soccer match-play on muscle strength injury risk factors have focused on different types of simulated match-play, either on treadmill (Greig, 2008; Rahnama et al., 2003) or overground (Cohen et al., 2014; Delextrat et al., 2010; Small et al., 2010). However, no previous studies have directly investigated the differences induced by each type of simulation, which is essessential if these studies are to be compared.

The primary objective of this present study was to compare the effects of match exertion induced by treadmill and overground simulated match-play on the conventional $H_{con} : Q_{con}$ and functional $H_{ecc} : Q_{con}$ ratios, as well as the angles of peak torque in relation with the implications of ACL injury risk. The null hypothesis was that there would be no differences in all concentric and eccentric muscle peak torques, $H_{con} : Q_{con}$ and $H_{ecc} : Q_{con}$ ratios, and angles of peak torque between the treadmill and overground match simulations.

5.3 Methods

5.3.1 Participants

A convenience sample of fifteen male recreational soccer players volunteered to participate in the study. Participants trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, body mass were 26 ± 4 years, 1.7 ± 0.1 m, 74 ± 8 kg, respectively. Participants were questioned on their injury history, none had previous ACL injury and all had been free from any other knee or thigh injury 6 months prior to testing. Written consent was obtained from all participants and the study was performed in accordance with the university ethics committee guidelines.

5.3.2 Experimental design

In a single group repeated measures design, participants were required to attend the laboratory at the same time of day on 3 separate sessions (one for familiarisation and two for testing). Participants attended the laboratory having been requested to perform no vigorous exercise or consume any alcohol or caffeine in the 24 hours prior to testing. During the familiarisation session, participants were familiarised with muscle strength assessment and performed both treadmill and overground match simulations for 10 min each. During the first testing session, and after completing a 15 min dynamic warm-up, participants were randomly assigned to perform either the treadmill or overground 45 min match simulation first. Before exercise (time 0 min), immediately at 'half-time' (time 45 min) and after 15 min 'half-time' rest (time 60 min) participants performed maximal quadriceps and hamstrings on the isokinetic dynamometer. During the 15 min 'half-time' period participants remained seated and were allowed to drink water. Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored every five minutes to monitor physiological changes. The second testing session was undertaken 4 to 8 days after the first testing session at the same time of the day.

5.3.3 Soccer match simulations

Full details of the 45 min overground and treadmill simulated match-play to replicate the exertion response of soccer match-play have been described in the Chapter 3 and 4.

5.3.4 Hamstrings and quadriceps strength assessment

Maximal torque generated by the hamstrings and quadriceps was measured on an isokinetic dynamometer (Biodex System 3, Shirley, NY; Figure 12). During testing, participants were seated on a dynamometer in an adjustable chair, with their trunk reclined at 85° and the test positions recorded and repeated for each participant in subsequent trials. Participants performed five maximal voluntary concentric quadriceps and hamstring actions, and five maximal voluntary eccentric hamstring actions using their dominant leg, which was determined as the leg used to kick a ball. The order of testing (concentric muscle contractions first, then eccentric contractions) was standardised for subsequent testing throughout the experimental trials. The crank axis was aligned with the axis of rotation of the lateral epicondyle of the knee using a passive resting position initially, which was then followed up by an active submaximal effort flexion extension movement during which the average position of the knee joint axis was qualitatively monitored to be as close as possible aligned with the crank axis. Previously suggested procedures to align both axes in an active resting position (Baltzopoulos, King, Gleeson, & De Ste Croix, 2012) were not followed due to measuring both flexion and extension contraction simultaneously. The cuff of the dynamometer's lever arm was secured around the ankle, approximately 5 cm proximal to the malleoli. Restraints were placed across the chest and the test thigh, proximal to the knee joint. Participants were instructed to grasp the handles next to the seat during maximal contractions. All actions were performed through a range of 0° to 90° knee flexion and extension (with 0° being a full knee extension) at an angular velocity of 120° $\cdot s^{-1}$. One minute of passive recovery was allowed between each trial. This test speed was selected as it has been shown to be acceptable as one of the fastest and safest speeds in which to reliably test eccentric hamstring muscle contractions (Rahnama et al., 2003; Small et al., 2010).

5.3.5 Data analyses

The isokinetic variables (peak torque) were extracted using custom algorithms created in Matlab (The MathWorks, Natick, MA, USA). Gravity-corrected peak torque values for the Q_{con}, H_{con} and H_{ecc} were quantified as the average of 5 trials that reached a joint angular velocity of 120° $\cdot s^{-1}$, for at least a range of motion of 70°, and within 10%

tolerance from the highest observed peak (Bossuyt, García-Pinillos, Raja Azidin, Vanrenterghem, & Robinson, 2015). The 5 torque-angle profiles were subsequently averaged using a 10-point smooth average with 1 degree resolution. The angle of peak torque was determined from this averaged torque-angle profile.

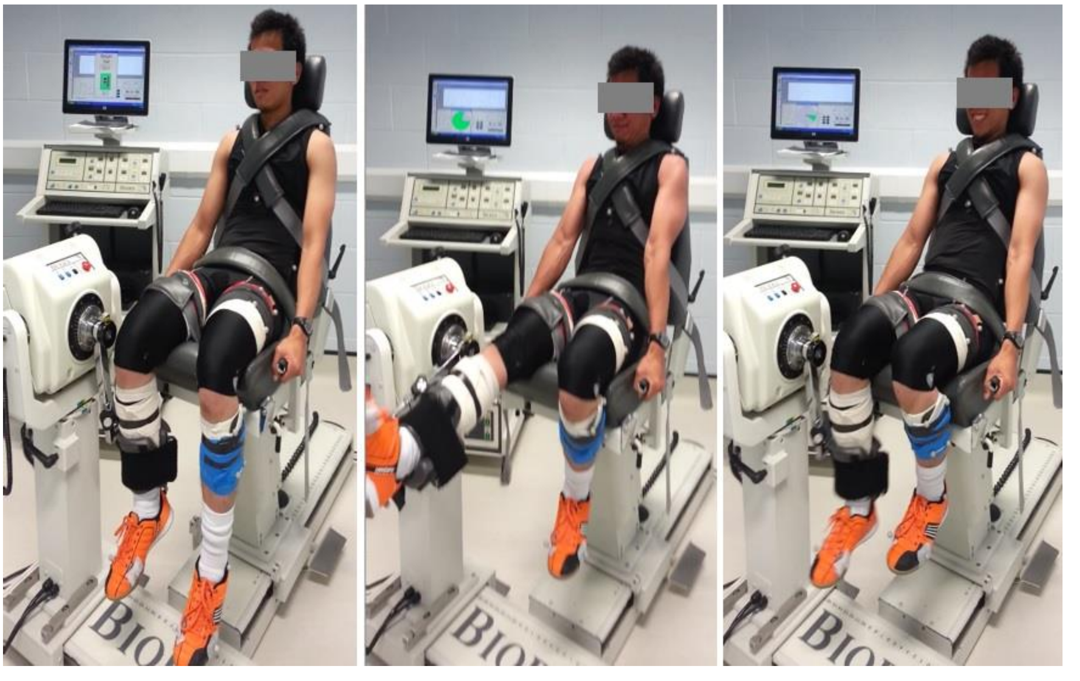

Figure 12. Hamstrings and quadriceps strength assessment using isokinetic dynamometer.

5.3.6 Statistical analyses

Means and standard deviations were calculated for each dependent variable. Paired t-tests were used to compare pre-exertion (time 0 min) conditions (overground vs. treadmill) to assess the baseline assumption of equality between simulations. Subsequently, a 2 (simulation: treadmill, overground) × 3 (time: 0 min, 45 min, 60 min) repeated measures analysis of variance (ANOVA) was conducted for each dependent variable using the statistical software package SPSS (Version 21; SPSS Inc., USA). Alpha was set at 0.05. Mauchly's test of sphericity was used to check for equality of variance between simulations and different times. If the Greenhouse–Geisser epsilon was >0.75 the Huynh

Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction value was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis.

5.4 Results

5.4.1 Physiological parameters

The mean heart rates during exercise (time 5 min to 45 min) for the treadmill and overground simulations were 140 ± 15 and 161 ± 10 beats · min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{3.2,57.8} = 10.2$, $P < 0.001$). While heart rates increased over time within each simulation ($P < 0.001$), the heart rates increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$). Similarly, the mean RPE during exercise (time 5 min to 45 min) was 12 ± 1 and 14 ± 1 for the treadmill and overground simulations respectively, with a significant interaction between simulation and time ($F_{3.5,63.5} = 14.8$, $P < 0.001$). While RPE increased over time within each simulation ($P < 0.001$), the RPE increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$).

5.4.2 Hamstrings and quadriceps peak torques

A significant interaction between simulations and time was observed in the Q_{con} peak torque ($F_{2, 28} = 4.134$, $P = 0.045$; Figure 13 a), Pairwise comparison revealed a significant difference between simulations at time 45 min ($P = 0.015$). However, there was no significant main effect in Q_{con} peak torque between simulations ($F_{1,14} = 4.314$, $P = 0.057$) or over time ($F_{2, 28} = 0.655$, $P = 0.527$).

For H_{con} peak torque, there was no significant interaction between simulations and time ($F_{2, 28} = 2.89$, $P = 0.072$) and no main effect between simulations ($F_{1,14} = 0.211$, $P = 0.653$) was observed. A significant effect of time was observed in the H_{con} peak torque

($F_{2,\ 28}$ = 5.78, P = 0.008) and pairwise comparison revealed a 4.7% reduction at time 45 min compared to time 0 min (P = 0.022; Figure 13 b).

A significant interaction between simulations and time was observed in the H_{ecc} peak torque ($F_{2,\ 28}$ = 3.548, P = 0.042). Pairwise comparison revealed a significant reduction in the overground simulation at time 45 min by 12.5% (P = 0.002) and time 60 min by 14.4% (P = 0.001) compared to time 0 min (Figure 13 c), and significant 5.2% reduction in the treadmill simulation only at time 60 min (P = 0.036).

5.4.3 Hamstrings and quadriceps strength ratio

The H_{con}:Q_{con} ratio revealed no significant changes during match simulations (Figure 14 a). However, significant changes were observed over time in the H_{ecc}:Q_{con} ratio ($F_{2,28}$ = 9.688, P = 0.001; Figure 14 b). Pairwise comparisons revealed a significant reduction from time 0 min to time 45 min by 7.4% (P = 0.026), and from time 0 min to time 60 min by 10.3% (P = 0.004).

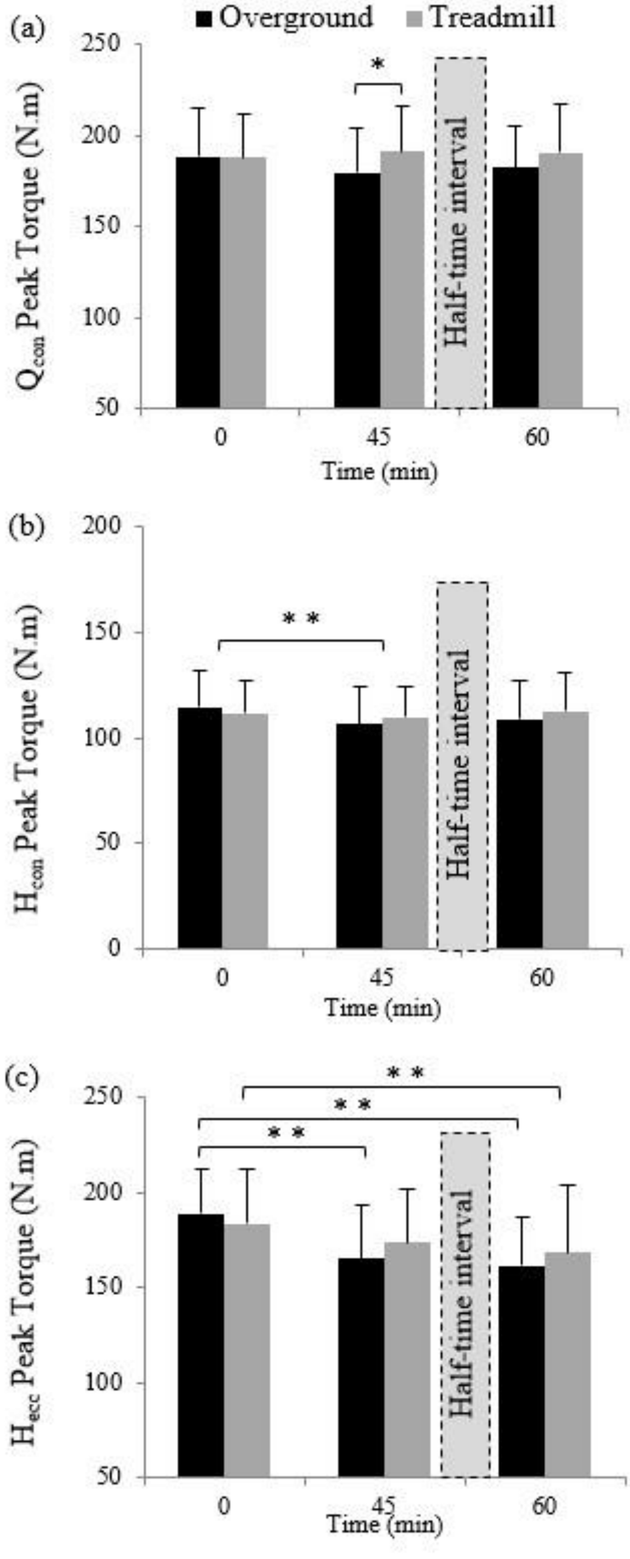

Figure 13. Quadriceps concentric peak torques (a) hamstrings concentric peak torques (b) and hamstring eccentric peak torques (c) during simulated match-play. *Indicates significant difference between simulations. **Indicate significant difference over time.

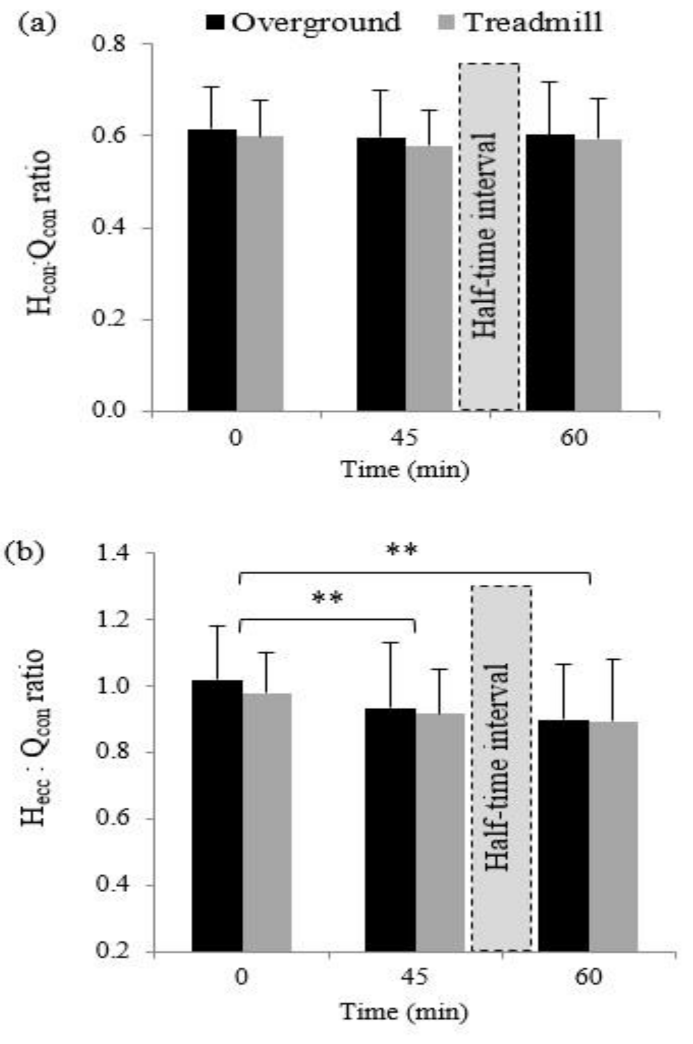

Figure 14. Conventional hamstring concentric: quadriceps concentric strength ratio (a) and functional hamstring eccentric: quadriceps concentric strength ratio (b) during simulated match-play. *Indicates significant difference over time.

5.4.4 Hamstrings and quadriceps angles of peak torque

No significant changes were observed between conditions and over time in H_{con} angle of peak torque (Figure 15 b) and H_{ecc} angle of peak torque during match simulations (Figure 15 c). However, significant changes were observed over time in the Q_{con} angle of peak torque ($F_{2,28}$ = 4.168, P = 0.026; Figure 15 a). Pairwise comparisons revealed a trend towards a 2.9% increase from time 0 min to time 45 min (P = 0.087) and a 2.8% increase from time 0 min to time 60 min (P = 0.053).

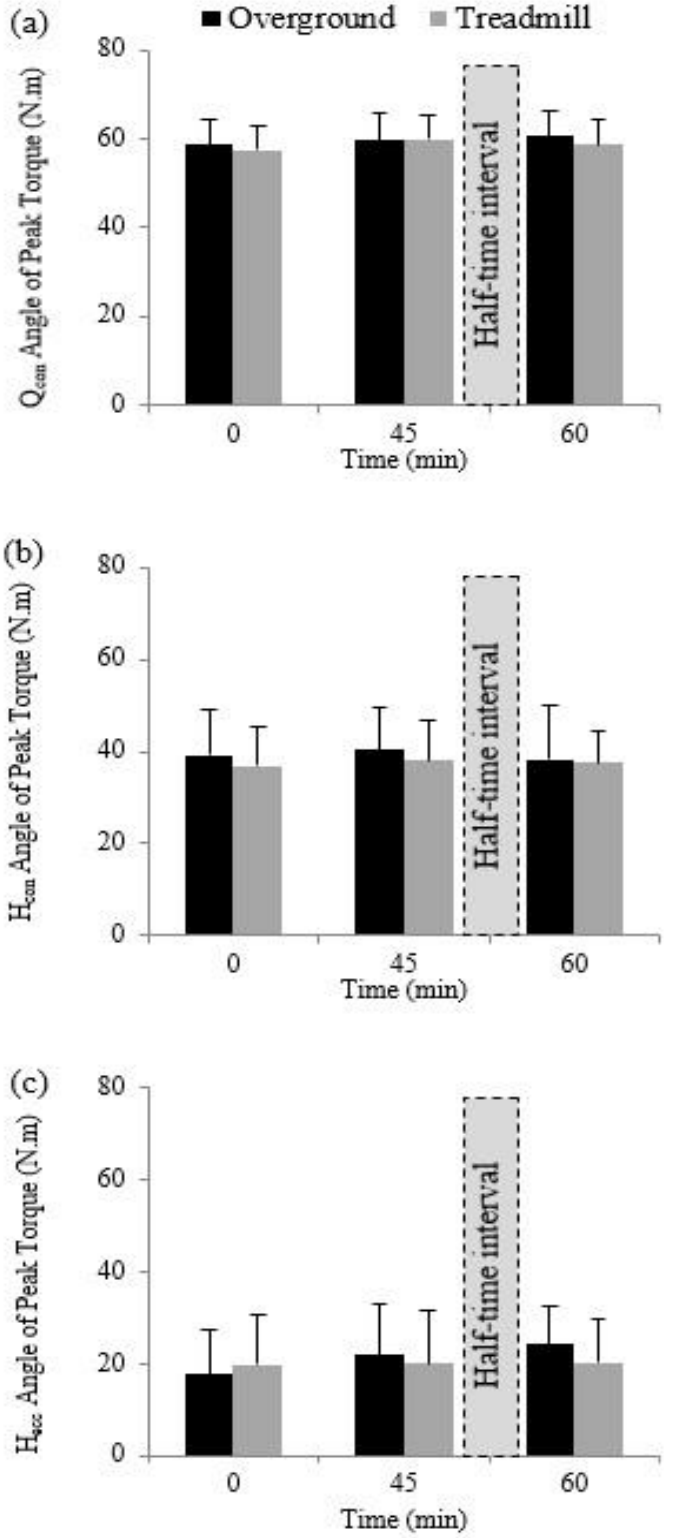

Figure 15. Quadriceps concentric angle of peak torques (a) hamstrings concentric angle of peak torques (b) and hamstring eccentric angle of peak torques (c) during simulated match-play.

5.5 Discussion

The main findings of the present study indicate that overground simulation induced greater physiological changes and greater impairment in muscle strength compared to treadmill simulation. These changes have been theorised to increase the likelihood of ACL injury, which will be addressed below.

5.5.1 Effects of soccer match simulations on physiological parameters

The study observed that the overground simulation induced greater physiological responses compared to the treadmill simulation, supporting Chapters 3 and 4 and justify the use of overground simulations for replicating the demands of soccer, more so than treadmill simulations.

5.5.2 Effects of soccer match simulations on muscle strength

The results from this study indicated that both the treadmill and overground simulation showed no changes when comparing conventional H_{con} : Q_{con} ratio. Similar findings have been reported with other studies (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Small et al., 2010), whilst in one study, an 10% reduction in H_{con} : Q_{con} ratio has been reported (Rahnama et al., 2003) after 45 min of treadmill simulation. It has been suggested that this reduction is mainly related to the significant reduction in H_{con} peak torque compared to the quadriceps, which was also observed in our study. The high proportion of type II muscle fibres in the hamstring (Garrett, Califf, & Bassett, 1984), characterised by a greater fatigability makes hamstrings more vulnerable during long duration exercises. Rahnama et al. (2003) also observed an 8% reduction in Q_{con} peak torque. This contradicts our finding which observed no change in Q_{con} peak torque with only significant interaction between simulations after 45 min. This discrepancy can be explained through difference in match simulation protocols. The treadmill simulation (Drust et al., 2000) employed by Rahnama et al. (2003) had a greater amount of time spent on high intensity cruising and sprinting, which may have induced greater physiological cost. In soccer, intense concentric contractions of the quadriceps are involved in particular at the start of a powerful movement such as sprinting or jumping, changes in direction or when kicking the ball (Delextrat et al., 2010). The results of the present study suggest that soccer match exertion does not jeopardise the capacity of the players to perform these specific movements at a maximal intensity.

In this present study, there were significant reductions in H_{ecc} peak torque after 45 min only in the overground simulation and at time 60 min in both simulations. The reduction in H_{ecc} contributed to greater impairment in functional $H_{ecc} : Q_{con}$ ratio (average 7.4%) than the conventional $H_{con} : Q_{con}$ ratio, although the mean values did not reach the lower limit of 0.7, which has previously considered indicative of a greater risk of injury (Aagaard et al., 1998). These findings were similar with other studies (Cohen et al., 2014; Delextrat et al., 2010; Small et al., 2010) and may indicate that overground simulation is more representative of a soccer match exertion compared to the treadmill simulation. Added to the higher proportion of type II muscle fibres in the hamstrings explaining a lower resistance to fatigue, the hamstrings musculature contracts primarily eccentrically during sprinting to decelerate the movement of the thigh and leg before foot contact (Bruckner & Khan, 2012; Sun et al., 2015). Their reduced capacity to decelerate the movement of the thigh at the same time impedes their capacity to counteract the anterior shear forces created by strong quadriceps contractions and with that their capacity to act as a knee stabilizer. This likely attributes to placing more stress on the ACL. Furthermore, the reduction in $H_{ecc} : Q_{con}$ ratio may also delayed or slow co-activation of quadriceps and hamstring muscles to provide an active protection for the knee and its passive restraints (Hashemi et al., 2011). These findings suggest the importance of injury prevention programme focusing on eccentric training for the hamstrings at the end of training session as it has been shown to be beneficial to maintain H_{ecc} peak torques and preserves H_{ecc} :

Q_{con} ratio throughout a simulated soccer match play (Small, McNaughton, Greig, Lohkamp, et al., 2009).

One interesting observation was the negative influence of the passive half time interval. During the half time interval, players remained seated, reflecting typical behaviour during competition. Our study revealed that in 15 minutes they failed to recover hamstring eccentric strength to pre-simulation values and failed to mediate the effect imposed during the first 45 min. Other studies investigating performance following half-time have similarly observed impaired physical performance such as sprinting time (Mohr et al., 2003) muscle strength (Small et al., 2010) and altered sprint (Small, McNaughton, Greig, & Lovell, 2009) and side cutting mechanics (Greig, 2009), which the authors attributed to lowered body temperature. These findings indicate that consideration should be given to active re-warm up strategies during the half-time interval which, as recently shown, would complement the physiological benefits associated with activity before the second half (Lovell et al., 2013) and potentially reduce the increased risk of injury observed during the early stages of the second half.

5.5.3 Effects of soccer match simulations on angle of peak torques

Our results demonstrated a trend towards significant increases over time in Q_{con} angle of peak torque in both simulations. This finding suggests a possible shift in the angle of peak torque in the direction of longer muscle lengths i.e. peak torque occurred when the knee was more flexed. This finding supports findings in Small et al. (2010), which they attributed to the “popping sarcomere hypothesis” (Morgan, 1990), causing a greater loss of relative force to occur at a shorter muscle length compared to optimum or long muscle lengths. This has been associated with muscle damage from eccentric contractions (Byrne, Eston, & Edwards, 2001). A good understanding of these mechanisms and their potential relationship to risk of ACL injury warrant further research.

No significant changes in H_{con} angle of peak torque and H_{ecc} angle of peak torque were observed in this study. This contradicts findings by (Small et al., 2010)who reported a significant 20% reduction in H_{con} angle of peak torque and a 23.2% increment in H_{ecc} angle of peak torque after 45 min of soccer match simulation. This may be explained by a difference in the method used to determining the angle of peak torque as we used a smoothed average over 5 trials, for better reproducibility rather than a single highest value (Sole, Hamren, Milosavljevic, Nicholson, & Sullivan, 2007).

5.5.4 Limitations

Several limitations are identified in this study. Firstly, the participants comprised of male recreational soccer players. Further studies would be needed to examine professional players as well as female players who are often cited as the most vulnerable to ACL injury. Secondly, this study has analysed peak torque and angle at which the peak torque is attained. This may limit the functional implications of our results because a high hamstrings eccentric torque would protect the knee joint only if it can be produced at a similar angle as the peak quadriceps concentric torque. Therefore, future studies might consider to further investigate the influence of soccer match exertion on the full torque angle profiles of these muscles.

5.6 Conclusions

To our knowledge, this was the first study to observe changes in muscle strength as markers of ACL injury risk, by directly comparing velocity-matched overground and treadmill simulated match-play. The overground simulation was observed to impose greater impairment in the dominant limb H_{ecc} peak torque. In addition, both simulations reduced H_{ecc}:Q_{con} ratio and generated a trend towards a shift in Q_{con} angle of peak torque in male recreational soccer players. These findings suggest a greater risk of ACL injury during the latter stages of first half and early stages of the second half, supporting epidemiological observations of increased injury rates. This study also suggests that the inclusion of simulated match-play as part of injury screening or return to sport assessment may provide critical information on how players may well be at increased risk of ACL injury from match-play induced detriments in muscular capacity.

Chapter 6

The Effects of Simulated Soccer Match-Play on Markers of Anterior Cruciate Ligament Injury in Females

6.1 Abstract

Fifteen healthy female participants completed a 45 min treadmill and overground match simulation with similar running velocity profiles. Prior to exercise (time 0 min), at half time (time 45 min) and 15 min post exercise (time 60 min) participants performed either five maximal dominant limb isokinetic contractions at 120°s^{-1} for Q_{con} and H_{ecc} or five trials of anticipated 45° side cutting manoeuvres. Heart rate and RPE were recorded every 5 min throughout the simulation. A two-way repeated measures ANOVA was used to identify significant differences between conditions and over time, with α=0.05. The heart rate and RPE were significantly greater during the overground than during the treadmill simulation. A significant time dependent reduction in H_{ecc} at time 45 min (9.3%), time 60 min (12%) and functional H_{ecc}:Q_{con} ratio at time 45 min (8.5%) was observed in the OG simulation only. There were no significant changes in Q_{con} and peak knee abduction moments during both simulations. These results suggest a greater risk of ACL injury in females at the end of the first half due to muscular imbalance rather than an adverse knee loading mechanism.

6.2 Introduction

High prevalence of non-contact anterior cruciate ligament (ACL) injuries has been observed in soccer, particularly in females. It is well established that female soccer players are 2 – 10 times more likely than male players to sustain ACL injuries (Agel, Arendt, & Bershadsky, 2005).

Current research investigating the effect of soccer match-play in females and its association with altered mechanics found that high levels of exertion lead to increased peak knee abduction moments (Tsai et al., 2009), and increased knee extension angles (Chappell et al., 2005; Cortes et al., 2013; Cortes et al., 2012; Lucci et al., 2011). Furthermore, Delextrat et al. (2011) have also examined female university soccer players, observed muscle strength imbalance impairments, in particular, reduced H_{ecc} strength and functional H_{ecc} : Q_{con} ratios, which have been theorised to increase the likelihood of ACL injury.

These studies have focused on different types of simulation protocols; either short –term high intensity exercises (Chappell et al., 2005; Cortes et al., 2013; Cortes et al., 2012; Tsai et al., 2009), simulated soccer match-play using treadmill (Greig, 2009), or an overground protocol (Delextrat et al., 2011; Lucci et al., 2011). In the previous chapters comparing the effect of treadmill versus overground match simulation in male soccer players, we found no significant changes in the knee biomechanical risk markers and observed a significant reduction in eccentric hamstrings strength only in the overground simulation. Both simulations were found to induce a reduction in functional H_{ecc} : Q_{con} ratio and a trend towards a shift in Q_{con} angle of peak torque. However, the mechanism surrounding the effects of soccer match-play in females is still poorly understood and whether treadmill and overground soccer match-play simulations induce similar responses in females remains unknown.

The objective of the present study was to compare the effects of match exertion induced by treadmill and overground soccer match simulations on knee mechanics and muscle strength imbalances in female soccer players. The null hypothesis was that there would be no differences in biomechanical (peak knee abduction moments at weight acceptance phase, knee extension angles at initial contact during side cutting) and muscle strength imbalance (Q_{con} strength, H_{ecc} strength, H_{ecc} : Q_{con} ratios, and angles of peak torque) between the treadmill and overground match simulations.

6.3 Methods

6.3.1 Participants

A convenience sample of thirteen healthy female recreational soccer players volunteered to participate in the study. Participants trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, body mass were 23 ± 3 years, 1.69 ± 0.06 m, 62 ± 4.9 kg, respectively. Participants were questioned on their injury history and none had previous ACL injury and all had been free from any other knee or thigh injury within the previous 6 months that could interfere with their performance of utility skills. Written consent was obtained from all the participants and the study was performed in accordance with the university ethics committee guidelines.

6.3.2 Experimental design

In a single group repeated measures design, participants were required to attend the laboratory for 5 separate sessions (one familiarisation and four testing). Participants attended the laboratory having been requested to perform no vigorous exercise or consume any alcohol or caffeine in the 24 hours prior to testing. During the familiarisation session, participants were familiarised with the cutting manoeuvre and the treadmill and overground match simulations for 10 min each. During the actual testing session, after completing a 15 min dynamic warm up, participants were randomly assigned to perform either a 45 min of treadmill or overground simulation. Before exercise (time 0 min), immediately at ‘half- time’ (time 45 min) and after 15 min ‘half-time’ rest (time 60 min), participants were randomly assigned to perform either a maximal quadriceps and hamstrings strength assessment on an isokinetic dynamometer or a 45° side cutting manoeuver involving biomechanical assessment. During the 15 min ‘half-time’ period participants remained seated and were allowed to drink water. Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored continuously every five min. The second testing session was undertaken 4 to 8 days after the first testing session, was conducted at the same time of the day, and participants completed the other 45 min match-play simulation.

6.3.3 Soccer match simulations

Full details of the overground and treadmill simulated match-play to replicate the exertion response of soccer match-play have been described Chapter 3 and 4. The only modification was that the total distance of the overground simulation and the average running speed in the treadmill simulation were reduced by 10% as female soccer players have been found to cover less distance and lower high intensity running during soccer a match compared to males (Mohr, Krustrup, Andersson, Kirkendal, & Bangsbo, 2008).

6.3.4 Assessment of side cutting kinematics and kinetics

To evaluate the biomechanical markers of ACL injury risk, three-dimensional marker trajectories were collected by 10 infrared cameras at 250 Hz (Oqus cameras, Qualisys, Gothenburg, Sweden) and forces collected by a 0.9 x 0.6 m force platform (Kistler, Winterhur, Switzerland) embedded in the floor, sampling at 1500 Hz. Full details of the kinematics and kinetics assessment procedures are described in the Chapter 4 and elsewhere (Malfait et al., 2014).

6.3.5 Hamstrings and quadriceps strength assessment

Maximal torque generated by the hamstrings and quadriceps was measured on an isokinetic dynamometer (Biodex System 3, Shirley, NY). Full details of the strength assessment procedures are described in the Chapter 5.

6.3.6 Statistical analyses

Mean and standard deviation were calculated for each dependent variable. Paired t-tests were used to compare pre-exertion (time 0 min) conditions (simulation: treadmill vs overground) to assess the baseline assumption of equality between simulations. Subsequently, for side cutting kinematics and kinetics, strength assessment of the hamstring and quadriceps assessment, a 2 (simulation: treadmill, overground) × 3 (time: 0 min, 45 min, 60 min) repeated measures analysis of variance (ANOVA) was conducted for each dependent variable using the statistical software package SPSS (Version 21; SPSS Inc., USA). The dependent variables included: peak knee abduction moments at weight acceptance phase, knee extension angles at initial contact, Q_{con} peak torque, H_{ecc} peak torque, $H_{ecc} : Q_{con}$ ratios, Q_{con} angle of peak torque and H_{ecc} angle of peak torque. Mauchly's test of sphericity was used to check for equality of variance between simulations and observation times. If the Greenhouse–Geisser epsilon was >0.75 the Huynh Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis. The alpha level was set at 0.05.

6.4 Results

6.4.1 Physiological parameters

The mean heart rates during exercise (time 5 min to 45 min) for the treadmill and overground simulations were 139 ± 3 and 164 ± 5 beats · min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{3.6,43.3} = 21.8$, $P < 0.001$). While heart rates increased over time within each simulation ($P < 0.001$), the heart rates increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$). Similarly, the mean RPE during exercise (time 5 min to 45 min) was 12 ± 1 and 13 ± 2 for the treadmill and overground simulations respectively, with a significant interaction between simulation and time ($F_{3.9,46.5} = 6.9$, $P < 0.001$). While RPE increased over time within each simulation ($P < 0.001$), the RPE increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$).

6.4.2 Effects of soccer match simulations on biomechanical markers of ACL injury

In the peak knee abduction moments, there was no significant interaction between simulation and time ($F_{1.4,16.8} = 0.66$, $P = 0.478$; Figure 16 a and 17 a). Similarly, no significant differences between simulations ($F_{1,12} = 1.21$, $P = 0.293$) or over time ($F_{1.3,15.9} = 1.22$, $P = 0.302$) were observed. There was also no significant interaction between simulation and time ($F_{1.4,16.6} = 3.32$, $P = 0.075$; Figure 16 b and 17 b), or any significant differences between simulations ($F_{1,12} = 0.457$, $P = 0.512$) or over time ($F_{1.8,21} = 2.77$, $P = 0.091$) in knee extension angles at initial contact.

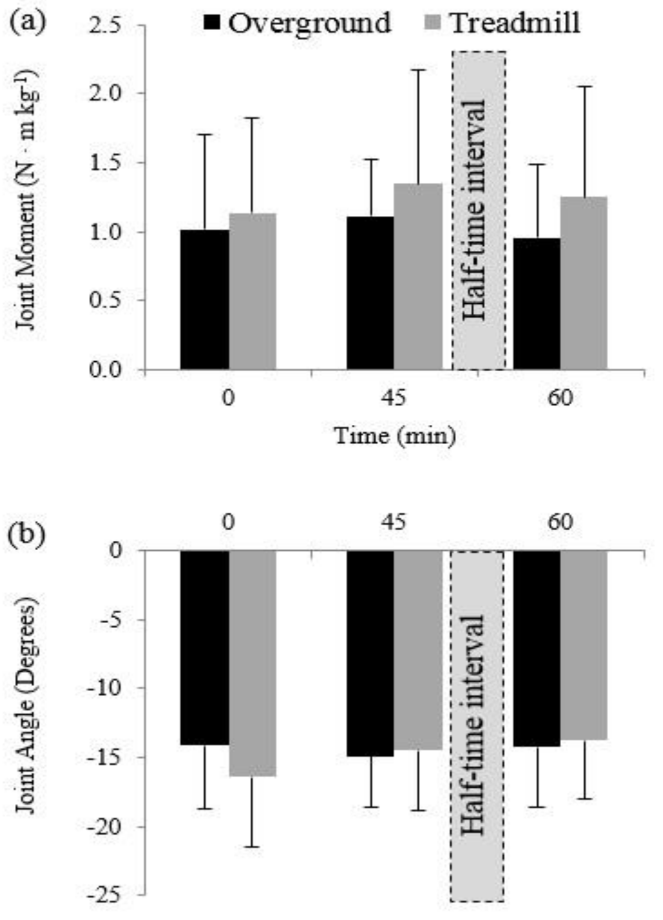

Figure 16. Peak knee abduction moments (a) and knee extension angles (b) during treadmill and overground simulation.

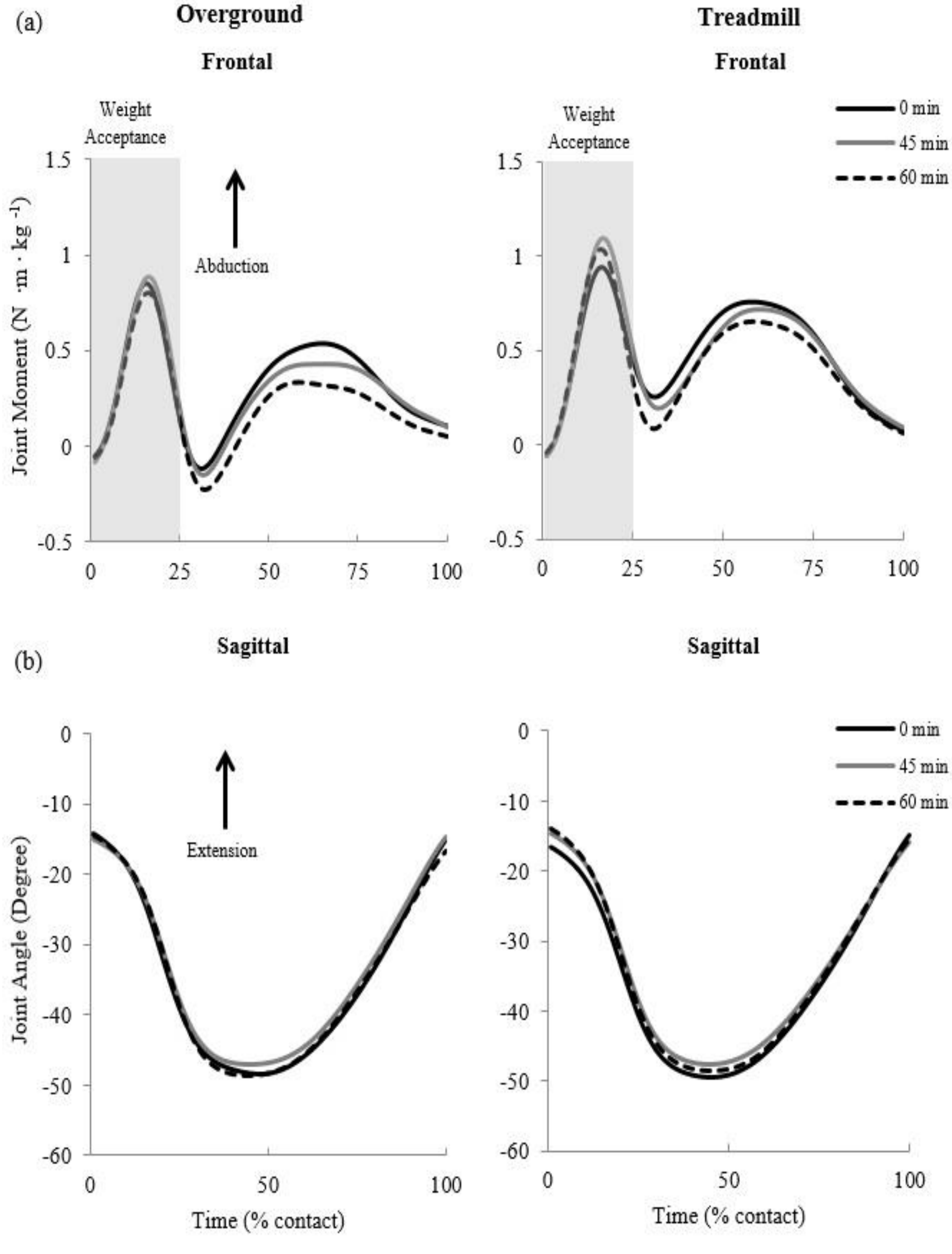

Figure 17. Knee abduction moments at weight acceptance phase (a) and knee extension angles at initial contact (b) during treadmill and overground simulation.

6.4.3 Effects of soccer match simulations on hamstrings and quadriceps strength related markers of ACL injury

For Q_{con} peak torque, no significant interaction between simulations and time ($F_{2,24} = 1.66$, $P = 0.212$) and no main effect between simulations ($F_{1,12} = 0.322$, $P = 0.581$) was observed. However, a significant change was observed over time ($F_{2,24} = 4.40$, $P = 0.024$). Pairwise comparison revealed a 3.7% reduction at time 60 min compared to time 45 min ($P = 0.008$; Figure 18 a). No significant interaction between simulations and time ($F_{1.8,21} = 2.13$, $P = 0.148$) and no main effect between simulations ($F_{1,12} = 3.02$, $P = 0.108$) was observed in H_{ecc} peak torque. A significant effect of time was observed in the H_{ecc} peak torque ($F_{2,24} = 7.09$, $P = 0.004$), and pairwise comparison revealed a reduction at time 45 min (6.3%; $P = 0.030$) and time 60 min (7.3%; $P = 0.023$) compared to time 0 min (Figure 18 b).

The functional H_{ecc}:Q_{con} ratio revealed no significant interaction between simulations and time ($F_{2,24} = 0.737$, $P = 0.489$) and no main effect between simulations ($F_{1,12} = 2.63$, $P = 0.131$). However, a significant change was observed over time ($F_{2,24} = 8.24$, $P = 0.002$). Pairwise comparison revealed a reduction of 7.9% at time 45 min compared to time 0 min ($P = 0.007$; Figure 18 c). No significant changes were observed between conditions and over time in Q_{con} angle of peak torque and H_{ecc} angle of peak torque during match simulations ($P > 0.05$; Figure 19 a and 19 b).

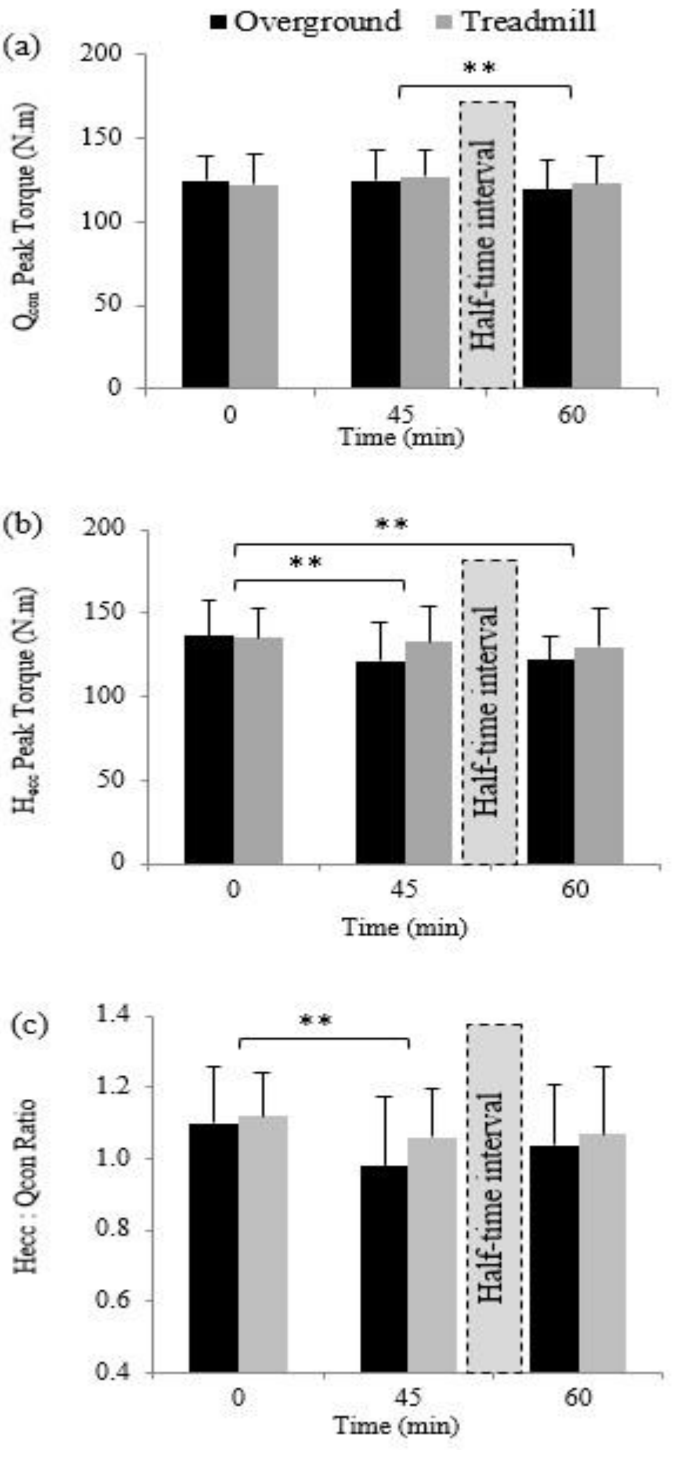

Figure 18. Quadriceps concentric peak torques (a) hamstrings eccentric peak torques (b) and functional hamstring eccentric: quadriceps concentric strength ratio (c) during simulated match-play. **Indicates significant difference over time.

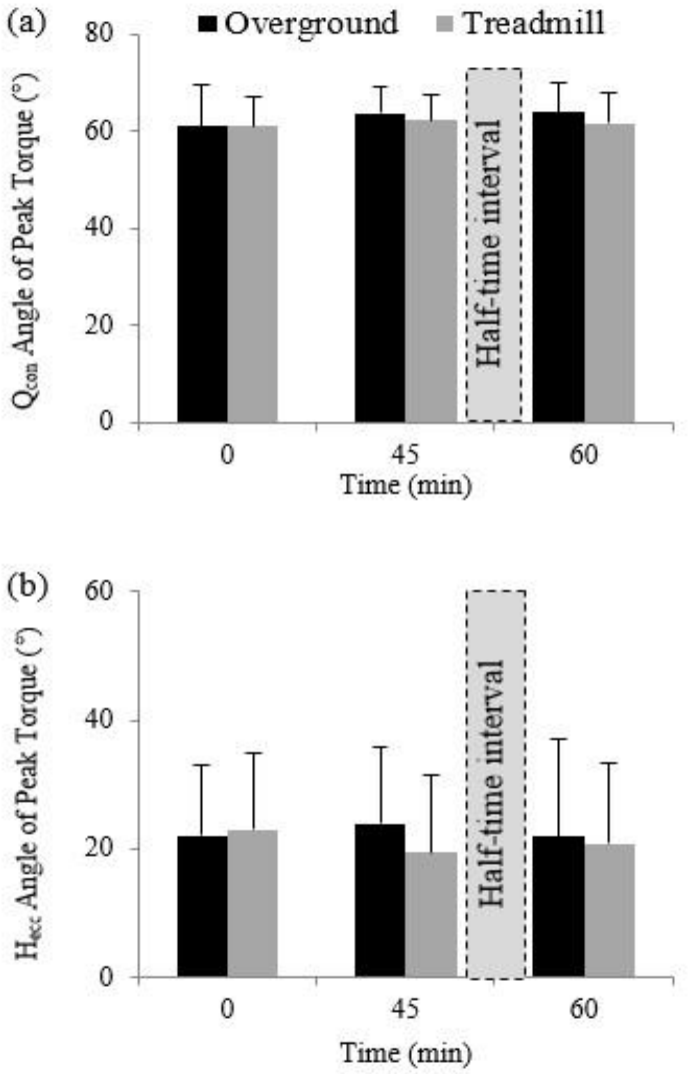

Figure 19. Quadriceps concentric angle of peak torques (a) and hamstring eccentric angle of peak torques (b) during simulated match-play.

6.5 Discussion

The main findings of the present study indicated that although overground simulation induced greater physiological changes compared to treadmill simulation, similar reduction in H_{ecc} and functional H_{ecc}:Q_{con} ratio have been observed in both simulations. These changes have been theorised to increase the likelihood of ACL injury, which will be addressed below.

6.5.1 Effects of soccer match simulations on physiological parameters

Our results show that the overground simulation induced greater physiological responses compared to the treadmill simulation. These findings were similar to our previous findings in Chapters 3 and 4, and previous values reported from actual match-play in females (Krustrup, Zebis, Jensen, & Mohr, 2010) and justify the use of overground simulations for replicating the demands of soccer in females, more so than treadmill simulations.

6.5.2 Effects of soccer match simulations on biomechanical markers of ACL injuries

Our results indicated that both treadmill and overground simulation showed no significant changes in peak knee abduction moments. Previous studies have indicated inconsistent outcomes on peak knee abduction moments after exertion. While some studies observed an increase in peak knee abduction moments (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009), others have observed no significant changes after simulation (Cortes et al., 2012; Lucci et al., 2011). This inconsistency can be explained through differences in type of simulation and task utilised. Firstly, those studies which observed increased peak knee abduction moments utilised high intensity, short duration (< 10 min) exercises designed to induce a level of volitional exhaustion. Secondly, as anticipated side cutting is a relatively simple task, participants may have retained sufficient ability to complete the manoeuvre without excessively loading the knee joint.

Our study also observed no significant effects on the knee extension angle at initial contact in both simulations. This finding is consistent with Sanna and O'Connor (2008) whilst in other studies a more extended knee during initial contact has been reported (Cortes et al., 2012; Lucci et al., 2011). This discrepancy may be explained again by the above mentioned differences in type of simulation and task utilised.

6.5.3 Effects of soccer match simulations on isokinetic parameters

No significant effects on Q_{con} strength was observed following match simulations. Similar findings have been reported with other studies in female (Delextrat et al., 2011) and male soccer players (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Small et al., 2010). In soccer, intense quadriceps concentric contractions are involved at the start of an explosive movement such a jumping, sprinting, changing direction, or when kicking the ball. Within this context, the results of the present study suggest that in females, like in males, exertion induced by match simulations does not negatively influence the capacity to perform these specific movements at a maximal intensity.

Significant reductions in H_{ecc} strength (averaging 6.3%) were observed following match-play in both conditions, supporting other female studies using a similar 120° $\cdot s^{-1}$ angular velocity (Delextrat et al., 2011). These reductions in H_{ecc} strength could be explained by a high proportion of type II muscle fibres that are characterised by lower resistance to fatigue (Garrett et al., 1984) and greater involvement of hamstrings eccentric contractions during both simulated match-play. Eccentric contractions of the hamstrings are also needed to assist the ACL in stabilizing the knee joint during explosive knee extensions performed when sprinting, jumping, or kicking the ball (Draganich & Vahey, 1990). Significant reductions in functional H_{ecc} : Q_{con} ratio (averaging 7.9%) were observed following match-play in both conditions, supporting other study (Delextrat et al., 2011). Whilst quadriceps capacity remained intact over time, the reduced hamstrings capacity can lead to reduced capacity to act as a knee stabilizer, adding more stress on the ACL. This may help explain the reported increased predisposition to injury during the latter stages of match play (Ekstrand et al., 2011; Hawkins et al., 2001).

Our study indicated that both match simulations showed no difference in Q_{con} and H_{ecc} angle of peak torques. This is in contrast to our previous study (Chapter 5) in male players where a trend towards significant increment was observed (2.9%), and to another study where a significant 20% increment in Q_{con} angle of peak torque and a 23.2% increment in H_{ecc} angle of peak torque after 45 min of soccer match simulation were reported (Small et al., 2010). The lack of changes in the angle of peak torque after simulated match-play in females may be explained by our lower limb selection. To align with our previous study in males, we also tested female participants on their dominant limb. Contrary to males however, females have been shown to more likely injure the ACL in their non-dominant limb (Brophy et al., 2010). This may suggest that exertion induced by match-play does not negatively influence the angles of peak torque in the dominant limb of female soccer players. Whether a negative influence of match-play on angles of peak torque may exist in the non-dominant limb requires further investigation.

Similar negative influences of the passive half time interval were observed in this study compared to our previous studies in males (Chapters 4 and 5). A further decrease in Q_{con} strength was observed after 15 minutes of passive rest and the participants also failed to recover H_{ecc} strength to pre-simulation values, supporting other studies in male soccer players (Greig, 2008; Small et al., 2010). Our study suggests that this inability to recover is also present in females, and that similar consideration should be given to intervention strategies during the half-time interval in female soccer players.

6.5.4 Limitations

In the present study, neither simulations incorporated a full match duration (90 minutes), and did not include actual ball handling skills (e.g., passing, dribbling, and heading) or interacting with an opponent. All observed movements in side cutting were also fully anticipated. Future research might consider the inclusion of unanticipated tasks in the match simulation, as well as the evaluation of biomechanical markers of injury risk during those unanticipated tasks.

6.6 Conclusions

To our knowledge, this was the first study to report changes in biomechanical and muscle strength markers of ACL injury risk in females, by directly comparing velocity-matched overground and treadmill simulated match-play. This study also was the first to examine the changes in angle of peak torques after simulated match-play in females. Both match-play simulations imposed greater impairment in the dominant limb H_{ecc} strength, and functional H_{ecc}:Q_{con} ratio. These findings suggest a greater risk of ACL injury during the latter stages of first half and early stages of the second half, supporting epidemiological observations of increased injury rates.

Chapter 7

Evaluating Markers of Anterior Cruciate Ligament Injury Risk during Simulated Soccer Match-Play: A Biomechanical and Isokinetic Investigation

7.1 Abstract

Eighteen male recreational soccer players completed a 90 min lab-based overground match-play simulation. Kinematics and kinetics of the support leg during unanticipated 45° side cutting manoeuvres were recorded as part of the simulated match-play, providing multiple trials within each 15 minutes interval. Participants also performed five maximal dominant-limb isokinetic contractions for Q_{con} and H_{ecc} prior to exercise (time 0 min), at the beginning and end of half-time (time 45 min and 60 min), and post-exercise (time 105 min). A one-way repeated measures ANOVA was used to identify significant differences over time, with α=0.05. Knee abduction moments were significantly reduced during the intervals 30-45, 60-75 and 90-105 min compared to the interval 0-15 min. The knee was significantly more extended at initial contact during the second half compared to interval 0-15 min. The hip was also significantly more extended in the last 15 minutes of simulated match-play. A significant reduction in H_{ecc} and functional H_{ecc}:Q_{con} ratio were observed at all times compared to pre-exercise values. The more erect landing posture at initial contact, reduced eccentric hamstring strength and muscle imbalances suggested a greater risk of ACL injury during the latter stage of match-play, supporting epidemiological observations and implying that screening during/after simulated match-play may be more effective in identifying increased ACL injury risk in soccer players.

7.2 Introduction

The high level of exertion during match-play has been speculated to be a key predisposition factor to injury (Ekstrand et al., 2011; Hawkins et al., 2001). Current research investigating soccer match-play and its association with altered mechanics, in particular related with peak knee abduction moments and knee extension angles, found that high levels of exertion lead to greater peak knee abduction moments (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009) and more extended knee angles during landing (Chappell et al., 2005; Cortes et al., 2012; Greig, 2009). Studies have also found extended hip angles during landing which are likely to generate higher load on the ACL (Cortes et al., 2012; Lucci et al., 2011).

Whilst in Chapters 4 and 6 we observed that knee mechanics were not altered during an anticipated side cutting task, studies have demonstrated that when task specifics are unanticipated until the very last moment, as is typical in match-play, loading is increased (Besier, Lloyd, Ackland, & Cochrane, 2001; Borotikar et al., 2008). The combination of exertions and unanticipated movement may reveal biomechanical risks which were not observed in our previous studies. In addition, most previous investigations only quantified changes following the match-play simulation. This does not reveal any temporal insights in how changes take place. Therefore, there is a need to understand how these selected markers of ACL injury risk are progressively affected during prolonged intermittent multidirectional simulation that is reflective of soccer demands. This may provide important insights on injury risk associated to the exertion of soccer match-play, and could help develop injury prevention programmes.

In Chapters 5 and 6, consistent reductions in H_{ecc} strength and functional H_{ecc} : Q_{con} ratio after match-play simulations have been observed, supporting other studies (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Rahnama et al., 2003; Small et al., 2010). However, no changes have been found in angles of peak torque, which has also been speculated to play an important role in ACL injury (Cohen et al., 2014; Small et al., 2010). This may be explained by the duration of the simulation, which was only 45 min.

The main objective of the present study was to investigate the effects of 90 min simulated soccer match-play on knee and hip mechanics during unanticipated side cutting, and on muscle strength imbalances of the hamstrings and quadriceps. It was hypothesized that exertion induced by simulated match-play increases peak knee abduction moments during weight acceptance phase, as well as knee and hip extension angles at initial contact during side cutting. We further hypothesized that the match exertion induced a significant reduction in H_{ecc} strength and in H_{ecc} : Q_{con} ratio, and increase in angle of peak torque.

7.3 Methods

7.3.1 Participants

Eighteen healthy male recreational soccer players volunteered to participate in the study. Based on previous studies focusing on the effects of fatigue on lower limb mechanics (Borotikar et al., 2008; Chappell et al., 2005; McLean & Samorezov, 2009), it was estimated that a minimum sample size of approximately 15 participants was needed to achieve 80% statistical power with an alpha level of 0.05. Participants habitually trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, body mass were 26 ± 7 years, 1.8 ± 0.01 m, 77 ± 11 kg, respectively. Participants were questioned on their injury history and none had a previous ACL injury and all had been free from any other knee or thigh injury for the previous 6 months that could interfere with their performance of utility movements. Written consent was obtained from all participants and the study was performed in accordance with the university ethics committee guidelines.

7.3.2 Experimental design

In a single group repeated measures design, participants were required to attend the laboratory at the same time of day on 2 separate occasions (one familiarisation and one testing), separated by no more than 7 days. During the familiarisation session, participants were familiarised with muscle strength assessment and performed 10 min of the simulated soccer match-play along with the unanticipated side cutting manoeuvres. During the testing session, and after completing a 15 min dynamic warm-up, participants were assigned to perform 90 min of the simulated match-play interceded by a 15 min half time period (see Figure 20). During the simulation, participants performed eight trials of unanticipated 45° side cutting (open and cross over) prior to simulation and at every 15 min. Prior to exercise (time 0 min), at the beginning and end of half-time (time 45 min and 60 min), and post-exercise (time 105 min), participants also performed maximal dominant limb hamstrings and quadriceps contractions on an isokinetic dynamometer (Biodex System 3, Shirley, NY). Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored every five min.

7.3.3 Soccer match simulations

In Chapter 3, 4 and 5, we found that overground soccer match simulation induce similar physiological responses with actual match-play. Therefore, in this study the overground simulation was selected to induce soccer-specific exertions. A 15 minutes activity profile was developed and repeated six times over the 90 min duration (Figure 20). A full description of the simulated match-play has been previously reported in Chapter 3.

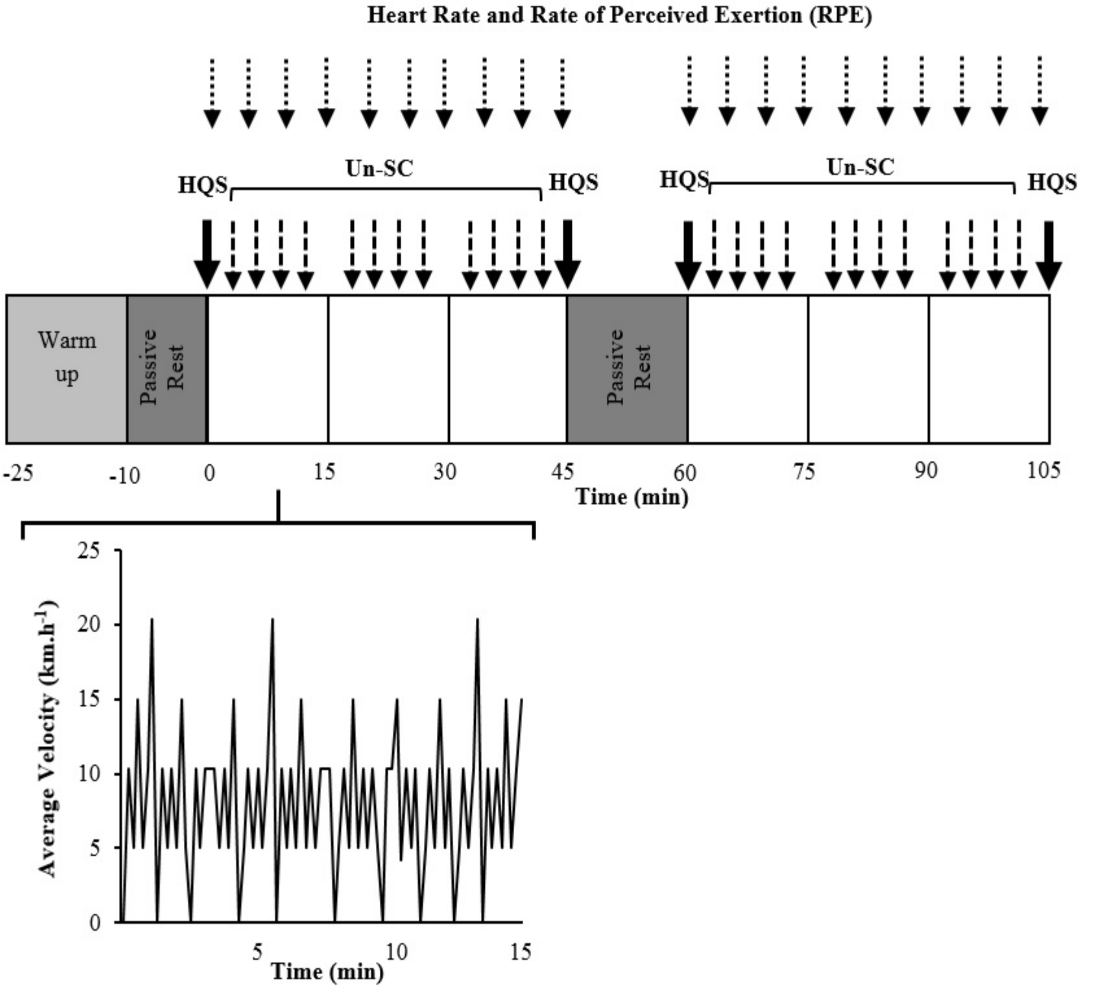

Figure 20. Schematic representation of the match simulation protocol and times of observations throughout: heart rate (HR), rate of perceived exertion (RPE), hamstrings and quadriceps strength (HQS), and unanticipated side cutting manoeuvres (Un-SC). Inset figure illustrates the 15-min velocity profile of the soccer match simulation protocol which was repeated three times for each 45-min half.

7.3.4 Assessment of side cutting kinematics and kinetics

Full details of the kinematics and kinetics assessment procedures are described in Chapter 4 and elsewhere (Malfait et al., 2014). The testing required the participants to perform two different unanticipated manoeuvres to replicate functional soccer movements, which included an open side cutting and a crossover step, both executed at 45° change of direction. The manoeuvres were performed using their dominant limb, which was determined as the limb used to kick a ball. When a timing gate 5 m prior to the force plate was interrupted, it triggered a custom made software programme (Mathlab, Math Works, Natick, MA. USA) to generate a visual cue in the form of an arrow on a screen in front of the participant, indicating which of the two manoeuvres to execute (side cutting or crossover step). The open side cutting involved a sudden change of direction to the left (if the participant is right foot dominant) at 45° from the initial approach, whilst landing with the right foot on the force platform (Figure 21, top). The cross over cut required the participants to change direction at 45° from the initial approach, whilst cutting across the body to the right with the right foot planted on the force platform (Figure 21, bottom). Participants had to perform four trials of each manoeuvre, a total of eight trials prior to exercise and eight times every 15 min during the simulation. The order of each 8 left/right trials was randomised to ensure 4 valid trials of each manoeuvre per 15 min of simulated match-play. The manoeuvres were performed at parts of the match simulation requiring the participant to run at 4.0 – 5.0 $m \cdot s^{-1}$, which is within a previously recommended approach speed (Vanrenterghem et al., 2012). For the purpose of this study, only the open sided cutting was analysed. Previous study has indicated that the open side cutting induced greater biomechanical injury risk due to less hip and knee flexion and greater knee abduction angles compared to crossover cuts (Potter et al., 2014).

7.3.5 Strength assessment of the hamstring and quadriceps

Maximal torque generated by the quadriceps and hamstrings was measured on an isokinetic dynamometer (Biodex System 3, Shirley, NY). Full details of the strength assessment procedures were described in Chapters 5.

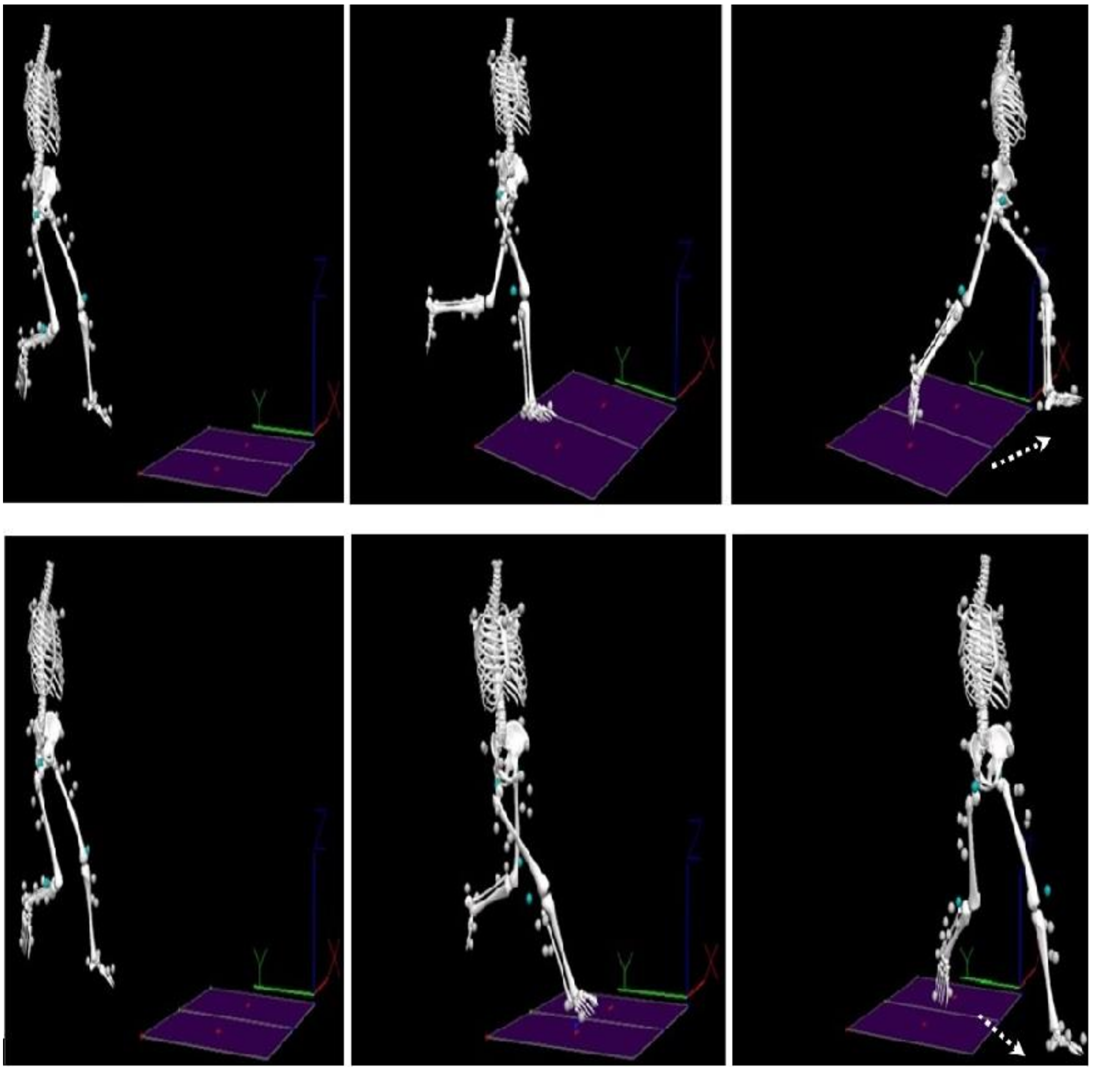

Figure 21. During match-play simulation, participants were required to perform an open side cutting (top) and a crossover step (bottom), both executed at 45° change of direction.

7.3.6 Statistical analyses

Descriptive statistics of outcome measures included means and standard deviations. Kinetic and kinematic parameters were averaged for each 15 min interval throughout the simulated match-play. A one-way repeated measures analysis of variance (ANOVA) was used to investigate the influence of exercise duration on each dependent variable using the statistical software package SPSS (Version 22; SPSS Inc., USA). The dependent variables used in this study included peak knee abduction moment, knee extension angles, hip extension angles, Q_{con} peak torques, H_{ecc} peak torques, functional H_{ecc} : Q_{con} ratio, Q_{con} angle of peak torque and H_{ecc} angle of peak torque. Mauchly's test of sphericity was used to check for equality of variance between simulations and different times. If the Greenhouse–Geisser epsilon was >0.75 the Huynh Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction value was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis and alpha level was set at 0.05.

7.4 Results

7.4.1 Physiological parameters

The mean heart rates and RPE during exercise were 159 ± 6 beats · min^{-1} and 14 ± 2 respectively. In addition, the resting heart rates and RPE were significantly lower compared with any time points during the simulation ($P < 0.001$).

7.4.2 Effects of soccer match simulation on biomechanical markers of ACL injury

A significant change in the peak knee abduction moments was observed over time during the simulation ($F_{3.8,64.9} = 6.25$, $P = 0.001$; Figure 22 a). Pairwise comparison revealed a significant reduction at time 30-45 min ($P = 0.043$), time 60 - 75 min ($P = 0.006$), and time 75 - 90 min ($P = 0.008$), compared to time 0-15 min. Knee extension angles changed significantly during the simulation ($F_{3.7, 62.5} = 7.42$, $P = 0.001$; Figure 22 b). Pairwise comparisons revealed that knee extension angles increased (became more extended) at time 60 - 75 min ($P = 0.004$), time 75 - 90 min ($P = 0.039$) and time 90 - 105 min ($P = 0.005$) compared to time 0 - 15 min. Hip extension angles changed significantly during simulation ($F_{2,35.4} = 6.77$, $P = 0.003$; Figure 22 c), with the hip extension angles being more extended at time 90 - 105 min compared to time 15 - 30, 30 - 45, and 60 - 75 min.

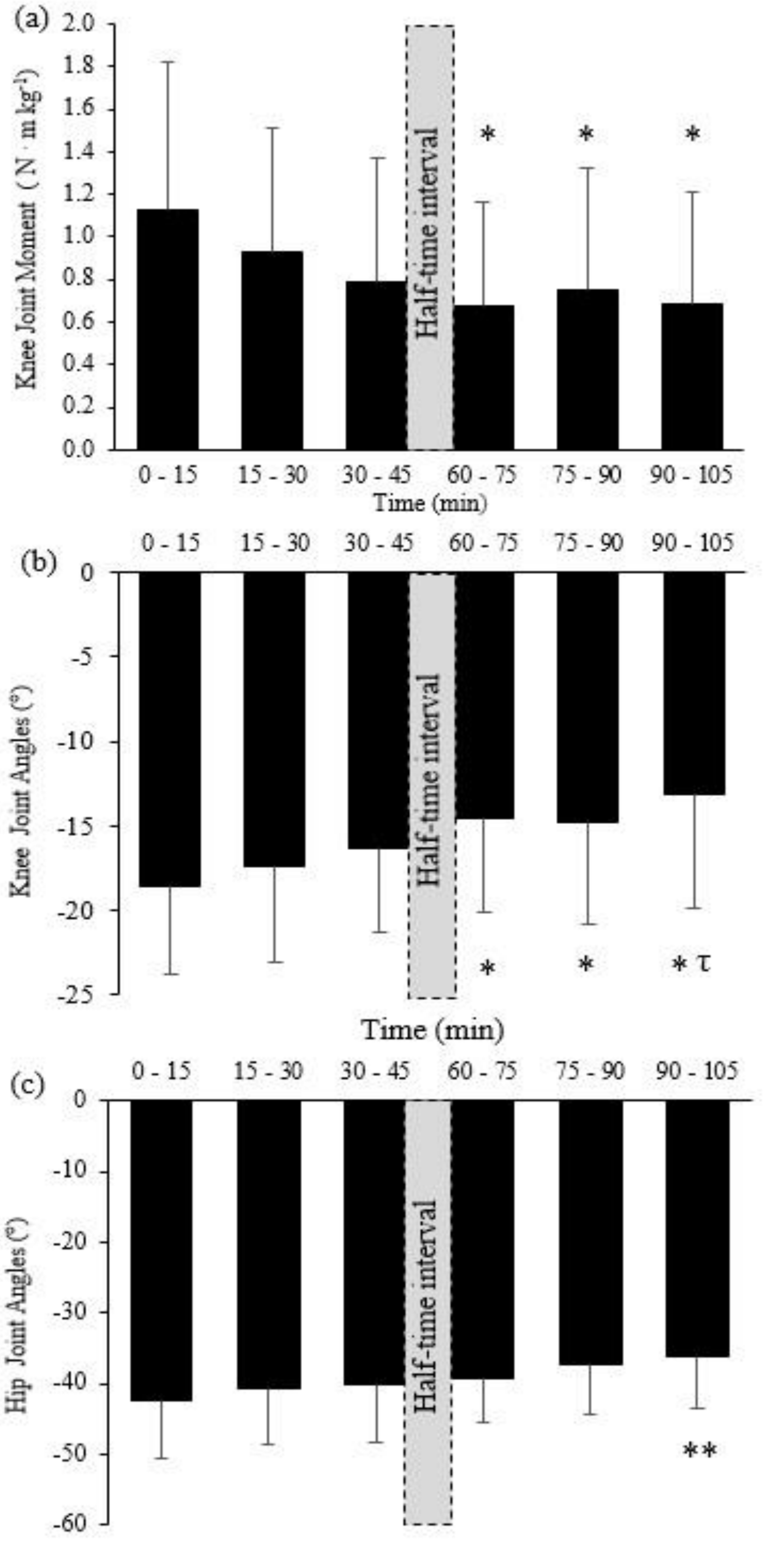

Figure 22. Peak knee abduction moments (a) knee extension angles (b) and hip extension angles (c) during match simulations. A joint angle of zero degrees indicates a straight leg.*Indicate significant different from time 0 - 15 min. ** Indicate significant different from time 15 - 75 min. $^{\tau}$ indicate significant different from time 15 - 30 min.

7.4.3 Effects of soccer match simulations on hamstrings and quadriceps strength related markers of ACL injury

The Q_{con} peak torque demonstrated a significant changes over time ($F_{3,51} = 3.82$, $P = 0.015$; Figure 23 a). However, pairwise comparison revealed only a trend in reduction was observed between time 0 min and time 60 min ($P = 0.068$). There was a significant difference in H_{ecc} peak torques during match simulation ($F_{2.78,\ 47.3} = 20.67$, $P < 0.001$; Figure 23 b). Pairwise comparison revealed significant reduction in H_{ecc} peak torques at time 45 min (12.7%; $P = 0.001$), time 60 (13.9%; $P = 0.001$) and, time 105 (20.9%; $P = 0.001$) compared with time 0 min. Similarly, a significant change was observed over time in the functional H_{ecc}:Q_{con} ratio ($F_{2,34.9} = 13.51$, $P = 0.001$; Figure 23 c). Pairwise comparison revealed these reduction was observed at time 45 min (10.5%; $P = 0.020$), time 60 (9.3%; $P = 0.0009$) and time 105 (18.1%; $P < 0.001$), compared with time 0 min. Although, the Q_{con} angle of peak torque demonstrated a significant increase with time ($F_{3,51} = 3.08$, $P = 0.036$; Figure 24 a), pairwise comparison revealed only a trend of increase was observed between time 0 min and time 105 min ($P = 0.090$). No significant differences in H_{ecc} angle of peak torque were observed (Figure 24 b).

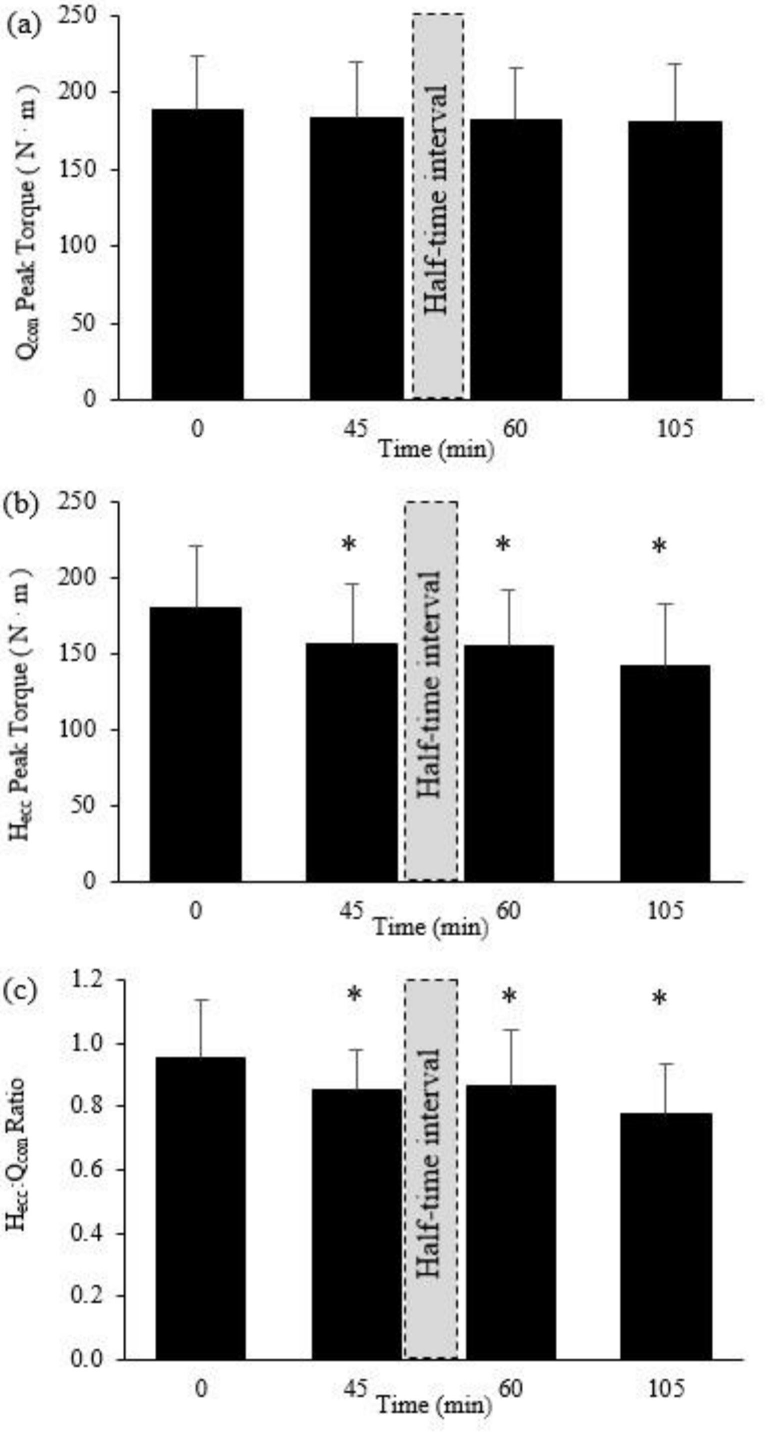

Figure 23. Quadriceps concentric peak torques (a) hamstrings eccentric peak torques (b) and functional hamstring eccentric: quadriceps concentric strength ratio (c) during simulated match-play. *Indicate significant difference from pre-simulation (time 0 min).

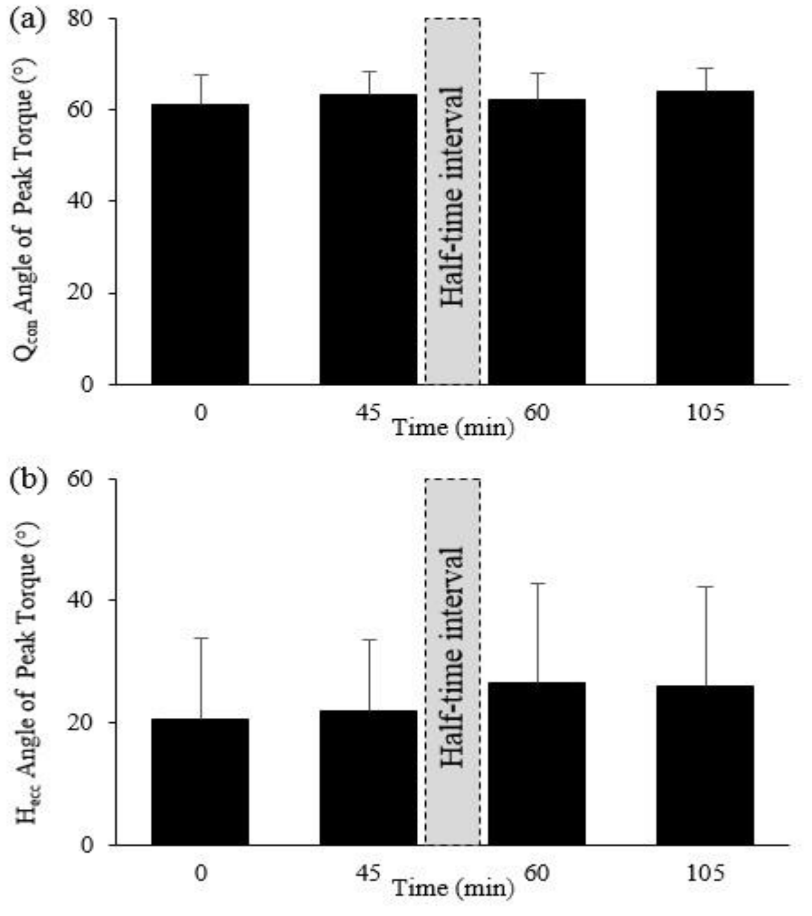

Figure 24. Quadriceps concentric angle of peak torques (a) and hamstrings eccentric angle of peak torques (b) during simulated match-play.

7.5 Discussions

The main findings of the present study indicate that male recreational soccer players performed unanticipated side cutting tasks with increasingly extended knee and hip joint angles at initial contact during simulated soccer match-play, and that they had reduced hamstrings eccentric peak torques and functional strength ratio during the latter stages of each half and at the start of second half. These changes support epidemiological observations and have been theorised to increase the likelihood of ACL injury. On the other hand, peak knee abduction moments reduced over time, which contradicts existing lines of thinking, and will be discussed below.

7.5.1 Effects of soccer match simulation on peak knee abduction moments

Our results indicated that exertion induced by match simulation showed a progressive reduction in peak knee abduction moments over time. Previous studies have indicated inconsistent outcomes on peak knee abduction moments after exertion. While some studies observed an increase in peak knee abduction moments (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009), others have observed no significant changes after simulation (Sanna & O'Connor, 2008). This discrepancy can be explained through differences in type of simulation, and different task protocols. Firstly, those studies which observed increased peak knee abduction moments utilised high intensity, short duration (< 10 min) exercises designed to rapidly induce a level of volitional exhaustion. Secondly, different task protocols employed by those studies utilised a two-leg jump task (Chappell et al., 2005; McLean et al., 2007). In our study, performing a 45° unanticipated side cutting manoeuvre during 90 min of multidirectional simulated match-play was believed to be more representative of the level of exertion and mechanical demands associated with actual match-play. Overall, although peak knee abduction moments have been recognised as a predictor of ACL injury, there remains no conclusive evidence that this variable is meaningful in explaining detrimental effects of match-play on risk of ACL injury in side cutting manoeuvres.

7.5.2 Effects of soccer match simulations on knee and hip extension angle at initial contact

In our study, the knee joint angle at initial contact became more extended and this continuously throughout the second half of match-play. Also the hip became significantly more extended during the final 15 min of second half, supporting other studies (Cortes et al., 2012; Greig, 2009) and epidemiological injury observations during actual soccer match (Ekstrand et al., 2011; Hawkins et al., 2001). Greig (2009) reported more extended knee angles (13° versus 30°) and the effect of the match-play simulation was more than what was observed in our study (5° versus 9°). The selection on the side cutting angles (180° in their study versus 45° in our study) may help explained the disparity. Although our observed change in 5° might not appear to be clinically relevant, we believe it is important when analysing how the knee responds to the demand of exertion induced by soccer match-play.

From a biomechanical perspective, we speculate that ACL injury risk increases with match-play due to an increasingly erect posture upon landing, and this especially in the second half when the highest level of exertion is reached. These movement adaptations may be caused by delayed or reduced co-activations of the hamstrings and quadriceps to provide active protection for the knees (Wojtys, Ashton-Miller, & Huston, 2002) and has been proposed as a contributor to ACL injury mechanisms (Hashemi et al., 2011). With the knee approaching nearly full extension at initial contact as a function of match-play exertion, we speculate that an increase in ACL loading occurs as the elevation angle of the ACL, patellar tendon insertion angle increases and a decrease in hamstrings insertion angle (Blackburn et al., 2008). These changes has been suggested to increase anterior tibial shear forces (Nunley, et al., 2003; Yu & Garrett, 2007), and limit the hamstrings' potential to counteract anterior tibial force to the ACL (Pandy & Shelburne, 1997). In addition, with the hip is more extended during landing, the load on the ACL increase and place the ACL at a greater risk of injury. Rather surprisingly, an increase in knee extension angle was associated with reduced peak knee abduction moments in our study, suggesting that a compensation strategy was employed by our male participants to avoid high frontal plan loading, and supporting the notion that sagittal plane injury mechanisms may be more relevant in males (Quatman et al., 2010). Other studies had found that female athletes who landed with a more extended knee (Pollard, Sigward, & Powers, 2010) and hip (McLean et al., 2005) increased their peak knee abduction moment. The discrepancy in the task protocols (drop landing versus side cutting) and sex differences (female versus male) makes direct comparisons to current data difficult.

Our study also observed a more extended knee immediately following the passive half-time interval, supporting findings from Chapter 4 and other studies (Greig, 2009). This might suggest an increased risk of injury during the initial stages of the second half and consideration should be given to prevention strategies during the half-time interval, such as active re-warm up, which could complement the performance benefits associated with activity before the second half (Lovell et al., 2013).

7.5.3 Effects of simulated match-play on isokinetic strength parameters

A significant reduction in H_{ecc} strength (averaging 13 - 21%) was observed following match-play simulation, supporting previous study in Chapter 5 and other studies using similar 120 $°\cdot s^{-1}$ angular velocity (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Rahnama et al., 2003; Small et al., 2010). These reductions in H_{ecc} strength could be explained by the greater involvement of hamstrings eccentric contractions during multidirectional, high accelerations and deceleration simulated match-play. As been previously explained, during high intensity activities of the simulated match-play (running, sprinting, turning), hamstrings contract eccentrically to decelerate the forward movements of the thigh and leg and to stabilize the knee in the late part of the swing phase just before the foot contact (Bruckner & Khan, 2012; Sun et al., 2015). In addition, a high proportion of type II muscle fibres in the hamstrings are characterized by a lower resistance to fatigue than quadriceps muscles with more type I muscle fibres (Garrett et al., 1984). In soccer, eccentric contractions of the hamstrings are also needed to assist the ACL in stabilizing the knee joint during explosive knee extensions performed when sprinting, jumping, or kicking the ball (Draganich & Vahey, 1990). A significant reduction in functional $H_{ecc} : Q_{con}$ ratio (averaging 18.1%) was observed following match-play in both conditions, supporting previous study in Chapter 5 and other studies (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Small et al., 2010). Insufficient strength can contribute to reduced capacity of the hamstrings to act as a knee stabilizer, adding more stress on the ACL, and may help explain the reported increased predisposition to injury during the latter stages of match play (Ekstrand et al., 2011; Hawkins et al., 2001). Therefore, the present finding suggests the need for soccer players to perform eccentric strengthening of the hamstrings, in particular post exertion from training and/or match-play, which has been shown to reduce the negative influence of match related exertion (Small, McNaughton, Greig, & Lovell, 2009).

Our study observed a trend towards significant changes in Q_{con} angle of peak torque following simulated match-play. The shift in Q_{con} angle of peak torque in the direction of longer muscle lengths has been suggested to potentially cause a significantly greater loss of relative force to occur at shorter muscle length compared to optimal or long muscle lengths, as associated with muscle damage from eccentric contractions (Byrne et al., 2001), and may increase susceptibility to muscle injury (Brockett, Morgan, & Proske, 2001). Our study did not observe any significant changes in H_{ecc} angle of peak torque. In contrast, other studies found significant changes in H_{ecc} angle of peak torque towards a shorter muscle length following simulated match-play (Cohen et al., 2014; Small et al., 2010). It has been proposed that peak torque developed at a shorter muscle length would mean that the muscle operating range is on the descending limb of the length-tension curve (Brughelli & Cronin, 2007), and coupled with the concurrent reductions in H_{ecc} strength, such reduced capacity to generate force at more extended knee joint angles may likely increase the risk of ACL injury.

7.5.4 Limitations

In our study, we were unable to determine the cause-and-effect relationship on the observed changes. The implications of the findings would be enhanced with the inclusion of electromyographic analyses of muscle co-activation patterns during the side cutting manoeuvres, which would further help to understand the role of match-play exertion as a potential contributor to ACL injury mechanisms (Hashemi et al., 2011). Furthermore, it may well be possible that further interrogation using Principal Component Analysis or Functional Data Analysis (Deluzio et al., 2004) may reveal more generalised effects of match simulation, and help understand the compensatory movement adaptations in male athletes that led to reduced knee joint abduction moments despite a more extended landing pattern.

7.6 Conclusions

The soccer match simulation was observed to induce changes in the knee and hip extension angles towards a more erect landing posture, and impaired eccentric hamstrings strength and muscle imbalances, despite reduced knee joint abduction moments. Overall, our findings suggest a greater risk of ACL injury during the latter stages of match-play and early stages of the second half, supporting epidemiological observations. Our findings also support the notion of injury risk screening during/after simulated match-play as it may be more effective in providing critical information on how match-play exertion contributes to ACL injury mechanisms in soccer players. Finally, impairments from altered knee mechanics and muscle strength imbalances during the early stages of second half warrant consideration of an acute intervention during the half-time interval to try and offset these.

Chapter 8

Does Re-Warm Up Influence the Markers of ACL Injury Risk during Multi-Directional Simulated Soccer Match-Play?

8.1 Abstract

Fourteen male recreational soccer players completed a 90-min lab-based multi-directional overground match-play simulation, comprising two 45-min halves separated by a 15-min half-time interval. During the half-time period, players either remained seated (passive, CON), or performed an intermittent agility exercise at ~70% of maximal heart rate during the last 5-min of half-time (re-warm up, RWU). Kinematics and kinetics of the support leg during unanticipated 45° side cutting manoeuvres were recorded as part of the simulated match-play, providing multiple trials over the 45 minutes which were subsequently grouped into 15 minute blocks. Participants also performed five maximal dominant-limb isokinetic contractions for concentric quadriceps (Q_{con}) and eccentric hamstrings (H_{ecc}) prior to exercise (time 0 min), at the beginning and end of half-time (time 45 min and 60 min), and post-exercise (time 105 min). A two-way ANOVA was used to identify significant differences, with α=0.05. Significant reductions in H_{ecc} and functional H_{ecc}:Q_{con} ratio were observed at all times during match-play compared to pre-exercise values, for both conditions, with no significant difference observed between conditions. A trend towards increased hip extension angles at initial contact was observed in the last 15 minutes of simulated match-play. No significant changes for Q_{con}, knee abduction moments and knee extension angles were observed. Re-warm up did not offset impairments in all the markers of ACL injury risk. Despite the growing evidence of physical performance improvement after RWU in soccer players, the efficacy of this intervention towards reducing ACL injury risks remains unknown and requires further investigation.

8.2 Introduction

In soccer match-play, the half-time interval is meant to allow players to physically and mentally recover from the strenuous activity, allowing them to start the second half with renewed energy. Nevertheless, there is evidence indicating reductions in physical performance related to total distance covered (Bangsbo et al., 1991) and distance covered at high speed (Mohr et al., 2003) during the initial phases of the second half of match-play.

A reduction in muscle temperature (approximately 1.5 – 2.0 °C) observed after the passive half-time interval (Lovell et al., 2013; Mohr et al., 2004) has been suggested as the primary mechanism, since increased muscle temperature has been shown to increase high intensity exercise performance due to increased neural potentiation (Gray, De Vito, Nimmo, Farina, & Ferguson, 2006). These findings indicate that consideration should be given to active re-warm up (RWU) strategies during the half-time interval. Recent work has shown that this can attenuate the reduction in muscle temperature and the associated reduction in sprinting, jumping, dynamic strength (Lovell et al., 2013), ball possession (Edholm et al., 2014) and soccer skills performance (Zois et al., 2013).

In Chapters 4, 5, and 7, we have observed a more extended knee at initial contact during side cutting and impaired eccentric hamstring strength after a passive half-time interval, suggesting a greater risk of ACL injury. Despite the physical benefits of RWU during the half-time interval, no studies have investigated the effectiveness of this intervention on markers of ACL injury risk.

The objective of the present study was to investigate the effect a half-time RWU has to reverse increased risk in the second half of play. It was hypothesized that RWU would offset impairments in the observed biomechanical markers of ACL injury risk in the second half of match-play, specifically related to greater knee and hip extension angles at initial contact during side cutting, or a greater peak knee abduction moment during the weight acceptance phase of side cutting. We further hypothesised that RWU would also offset impairments in the observed muscle strength related markers of ACL injury associated with reduced eccentric hamstring strength leading to increased hamstrings and quadriceps imbalance, and associated with altered angles of peak torque.

8.3 Methods

8.3.1 Participants

A convenience sample of 14 male recreational soccer players volunteered to participate in the study. Participants trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, and body mass were 26 ± 4 years, 1.8 ± 0.01 m, 80 ± 12 kg, respectively. Participants were questioned on their injury history and none had a previous ACL injury and all had been free from any other knee or thigh injury that could interfere with their performance of utility movements during the previous 6 months. Written consent was obtained from all participants and the study was performed in accordance with the university ethics committee guidelines.

8.3.2 Experimental design

In a single group repeated measures design, participants were required to attend the laboratory at the same time of day on 3 separate occasions (one familiarisation and two testing), separated by at least 4 days and no more than 7 days. During the familiarisation session, participants were familiarised with muscle strength assessment and performed 10 min of the simulated soccer match-play along with unanticipated side cutting manoeuvres. During the testing session, and after completing a 15 min dynamic warm-up, participants were assigned to perform 90 min of the simulated match-play interceded by a 15 min half time period (see Figure 25). During the 15 min half-time period players either remained seated (CON) or performed a re-warm up intervention of intermittent agility exercises during the final 5 min of half-time (RWU). Prior to match-play simulation, and as integral part of every 15 min of match-play simulation, participants performed eight trials of unanticipated 45° side cutting (open and cross over). Prior to exercise (time 0 min), at the beginning and end of half-time (time 45 min and 60 min), and post-exercise (time 105 min), participants also performed maximal dominant limb hamstrings and quadriceps contractions on an isokinetic dynamometer (Biodex System 3, Shirley, NY). Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored every five min.

8.3.3 Soccer match simulation

The same 90 min overground match simulation as in Chapter 7 was used in this study. A full description of the simulated match-play has been previously reported in Chapters 3 and 7.

8.3.4 Re-warm up intervention

Studies related with re-warm up during half-time rest interval (Edholm et al., 2014; Lovell et al., 2013; Mohr et al., 2004) have suggested that a short active re-warm up regime (~7 min intermittent agility exercises at 70% of HR_{max} as a component of the latter part of the 15 min half time period) is an efficient method to maintain elevated muscle temperature and preserve sprint and jump performance over half time period. However, whether this type of exercises and prescribed intensity can reduce the risk of ACL injury remains unknown. Therefore, in this study the RWU exercises incorporated intermittent agility drills (Lovell et al., 2013) using a 4 m agility ladder. The participants were asked to performed several agility drills (forward, sideways, slalom) at moderate to high speed (Figure 26). The duration of the rest interval was manipulated during the intervention to elicit ~70% of the peak heart rate (Mohr et al., 2004), which was pre-determined by identifying peak heart rate reached during the first half of match simulation.

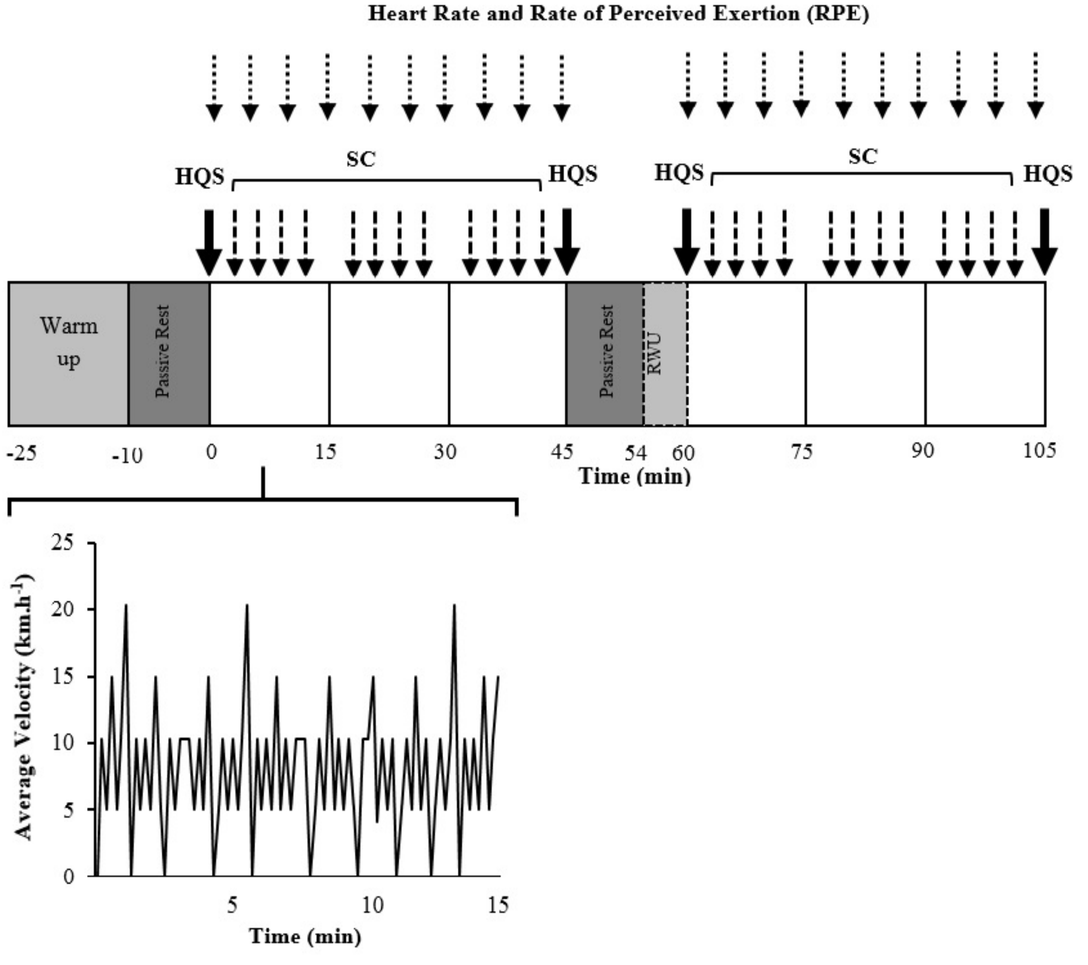

Figure 25. Schematic representation of the match simulation protocol and times of observations throughout: heart rate (HR), rate of perceived exertion (RPE), hamstrings and quadriceps strength (HQS), and unanticipated side cutting manoeuvres (SC). Inset figure illustrates the 15-min velocity profile of the soccer match simulation protocol which was repeated three times for each 45-min half. Re-warm up (RWU) was replaced by passive rest in the control condition.

8.3.5 Assessment of side cutting kinematics and kinetics

Full details of the kinematics and kinetics assessment procedures were described in Chapter 7 and elsewhere (Malfait et al., 2014).

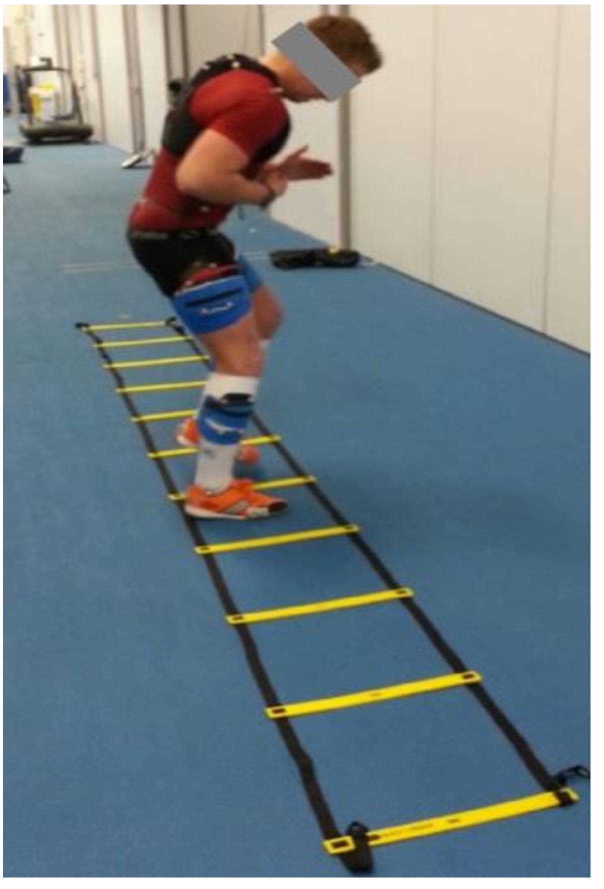

Figure 26. A participant performing re-warm up (sideways) exercise.

8.3.6 Strength assessment of the hamstring and quadriceps

Maximal torque generated by the quadriceps and hamstrings was measured on an isokinetic dynamometer (Biodex System 3, Shirley, NY). Full details of the strength assessment procedures were described in Chapters 5.

8.3.7 Statistical analyses

Mean and standard deviation were calculated for each dependent variable. Paired t-tests were used to compare pre-exertion (time 0 min) conditions (CON vs. RWU) to assess the baseline assumption of equality between simulations. Subsequently, for side cutting kinematics and kinetics assessment, a 2 (conditions: CON, RWU) × 6 (time: 0 - 15 min, 15 - 30 min, 30 - 45 min, 60 - 75 min, 75 - 90 min and 90 - 105 min) repeated measures analysis of variance (ANOVA) was conducted for each dependent variable using the statistical software package SPSS (Version 20; SPSS Inc., USA). For strength assessment of the hamstring and quadriceps, a 2 (conditions: CON, RWU) × 4 (time: 0 min, 45 min, 60 min and 105 min) ANOVA was conducted for each dependent variable. Mauchly's test of sphericity was used to check for equality of variance between simulations and different times. If the Greenhouse–Geisser epsilon was >0.75 the Huynh Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis. The alpha level was set at 0.05.

8.4 Results

8.4.1 Physiological parameters

The mean heart rates during exercise for RWU and CON were 161 ± 6 and 160 ± 6 beats $\cdot$ min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{15.6,203.55}$ = 28.5, P < 0.001). The heart rates increased over time within each condition (P < 0.001). Before the start of the second half (time 9 min, 12 min, and 15 min of half-time), the heart rate was significantly higher (P < 0.001) after RWU compared with CON.

Similarly, the mean RPE during exercise was 14 ± 2 and 13 ± 2 for the CON and RWU respectively, with a significant interaction between simulation and time ($F_{3.6,46.8}$ = 9.0, P < 0.001). While RPE increased over time within each condition (P < 0.001), the RPE increased significantly more for the RWU relative to the OG (P < 0.001) before the start of the second half (time 9 min, 12 min, and 15 min of half-time).

8.4.2 Effects of RWU on biomechanical markers of ACL injury

In the peak knee abduction moments, there was no significant interaction between condition and time ($F_{3.1, 40.3}$ = 0.14, P = 0.938; Figure 27 a), and no main effect between conditions ($F_{1, 13}$ = 2.50, P = 0.138). A significant main effect of time was observed ($F_{1.9, 25.4}$ = 5.06, P = 0.015), but not in pairwise comparisons. In the knee extension angles, there was no significant interaction between condition and time ($F_{3.7, 48.5} = 2.31$, $P = 0.075$; Figure 27 b). Similarly, no significant main effects between conditions ($F_{1, 13} = 0.85$, $P = 0.372$) or over time ($F_{2.5, 32} = 2.19$, $P = 0.119$) were observed. In hip extension angles at initial contact, there was no significant interaction between condition and time ($F_{1.65, 21.5} = 0.278$, $P = 0.718$; Figure 27 c), and no main effect between conditions ($F_{1, 13} = 1.04$, $P = 0.327$). However, a significant change was observed over time ($F_{2, 26} = 4.96$, $P = 0.015$). Pairwise comparisons revealed a trend towards an increased hip extension angle (became more extended) at time 90 - 105 min compared to time 60 - 75 min ($P = 0.078$).

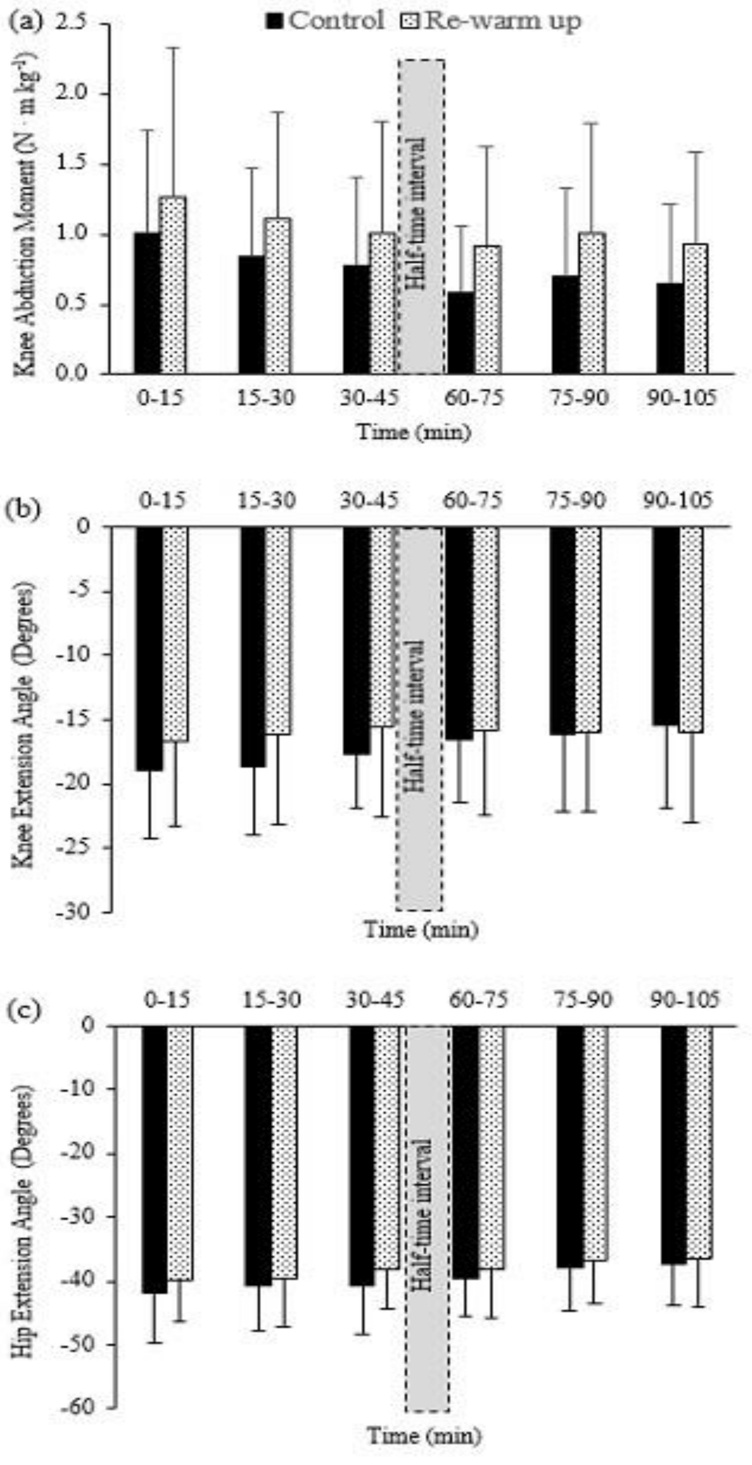

Figure 27. Peak knee abduction moments (a) knee extension angles (b) and hip extension angles (c) during match simulations. A joint angle of zero degrees indicates a straight leg.

8.4.3 Effects of RWU on hamstrings and quadriceps strength related markers of ACL injury

The Q_{con} revealed no significant changes during simulated match-play (Figure 28 a). For H_{ecc} peak torque, no significant interaction between condition and time ($F_{3, 38.8} = 0.94$, $P = 0.432$) and no main effect between conditions ($F_{1, 13} = 3.91$, $P = 0.069$). A significant effect of time was observed in the H_{ecc} peak torque ($F_{3, 39} = 36.89$, $P = 0.001$) and pairwise comparison revealed a significant reduction at time 45 min (12.5%; $P = 0.001$), time 60 min (10.4%; $P = 0.002$) and time 105 min (20.1%; $P = 0.001$) compared to time 0 min (Figure 28 b). Similarly, the H_{ecc}: Q_{con} ratio revealed no significant interaction between condition and time ($F_{2.9, 38.2} = 0.372$, $P = 0.770$) and no main effect between conditions ($F_{1, 13} = 4.19$, $P = 0.061$). A significant effect of time was observed in the H_{ecc}: Q_{con} ratio ($F_{3, 39} = 25.13$, $P = 0.001$) and pairwise comparison revealed a significant reduction at time 45 min (11.2%; $P = 0.022$), time 60 min (8.1%; $P = 0.015$) and time 105 min (18.4%; $P = 0.001$) compared to time 0 min (Figure 28 c).

The Q_{con} angle of peak torque revealed no significant interaction between condition and time ($F_{2.8, 37} = 1.80$, $P = 0.167$) and main effect between conditions ($F_{1, 13} = 0.241$, $P = 0.632$) was observed. A significant effect of time was observed in the Q_{con} angle of peak torque ($F_{3, 38.4} = 11.81$, $P = 0.001$) and pairwise comparison revealed a significant increase at time 45 min (5.1%; $P = 0.024$), time 60 min (4.1%; $P = 0.022$) and time 105 min (6.6%; $P = 0.001$) compared to time 0 min (Figure 29 a). There was no significant interaction between condition and time ($F_{3, 39} = 0.877$, $P = 0.832$), or main effect between conditions observed in H_{ecc} angle of peak torque ($F_{1, 13} = 0.047$, $P = 0.832$). A trend towards a significant effect of time was observed over time ($F_{2.2, 28.9} = 3.05$ $P = 0.058$). Pairwise comparisons revealed a significant increase at time 105 min (28.1%; $P = 0.037$) compared to time 0 min (Figure 29 b).

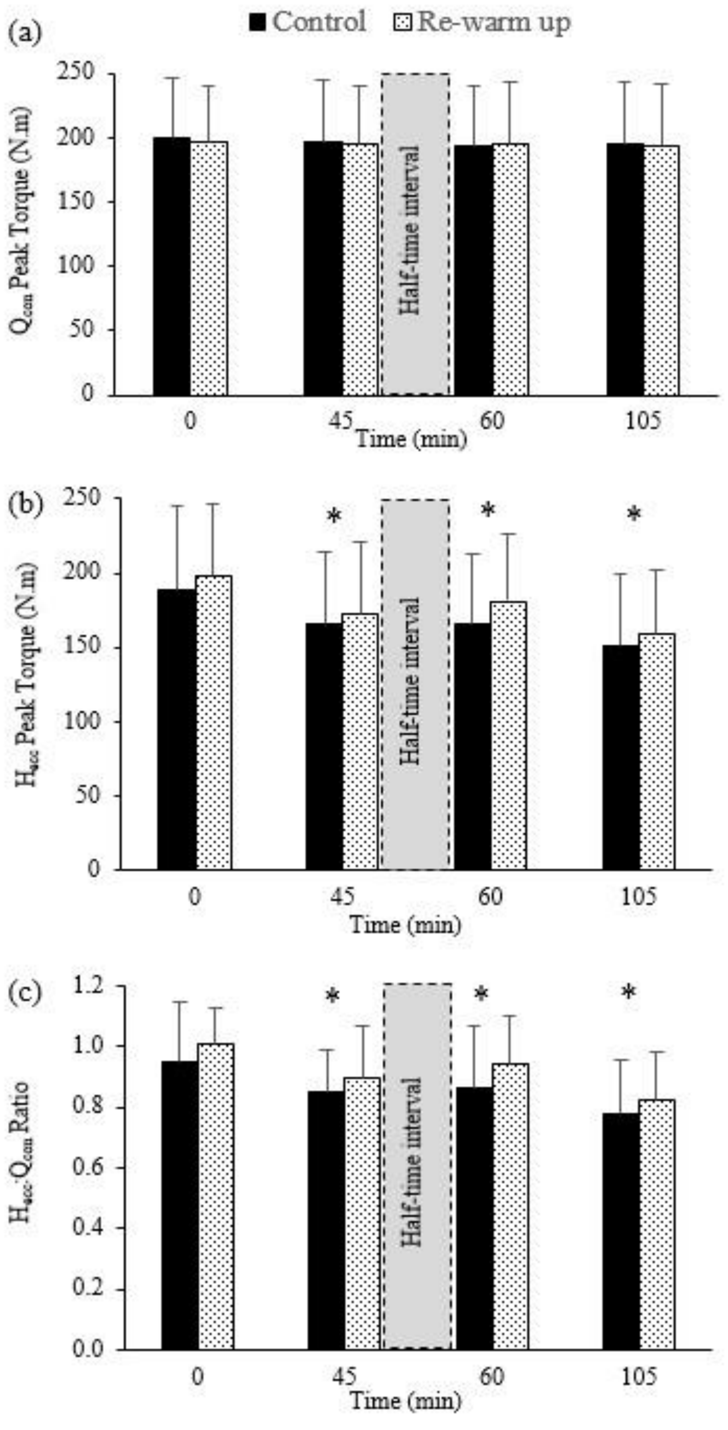

Figure 28. Quadriceps concentric peak torques (a) hamstrings eccentric peak torques and (b) functional hamstring eccentric: quadriceps concentric strength ratio (c) during simulated match-play. *Indicate significant difference from pre-simulation (time 0 min).

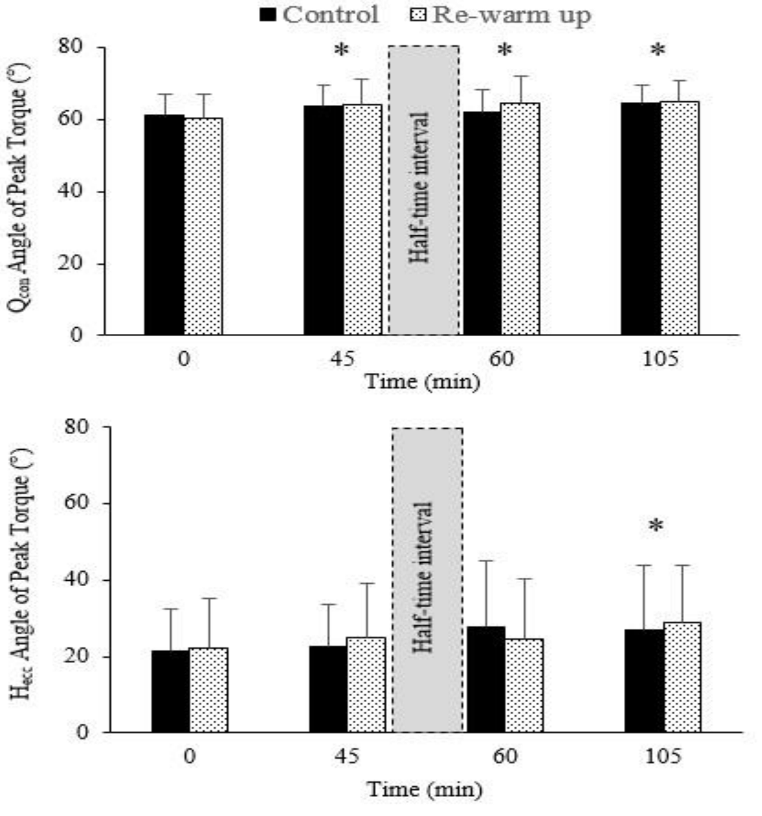

Figure 29. Quadriceps concentric angle of peak torques (a) hamstrings eccentric angle of peak torques (b) during simulated match-play. *Indicate significant difference from pre-simulation (time 0 min).

8.5 Discussions

The main findings revealed that RWU did not offset impairments in the observed biomechanical and muscle strength related markers of ACL injury.

8.5.1 Effects of RWU on biomechanical markers of ACL injuries

In the present study, no significant differences between the RWU and CON condition in all selected biomechanical markers of ACL injury were observed. Whilst the simulated match-play does not influence any changes in peak knee abduction moments, or knee and hip extension angles during the second half of match-play, we also did not observe any significant effect of RWU. Nevertheless, this study may provide the first insights on the biomechanical rationale to include RWU as part of injury prevention intervention.

Although previous studies have consistently found physical performance improvement after RWU (Edholm et al., 2014; Lovell et al., 2013; Mohr et al., 2004; Zois et al., 2013), perhaps those enhancements were not directly associated with reductions of ACL injury risk. In fact, an increase in high intensity running after RWU found in those studies may contribute to higher mechanical loading to the knee. However, we did not measure any physical performance parameters during the simulation to justify this claim. The lack of changes in the biomechanical markers of ACL injury risk can also relate with the RWU exercise selection. Previous studies have incorporated similar intermittent agility exercise, intermittent exposure to whole body vibration (Lovell et al., 2013), low to moderate intensity jogging, or light calisthenics exercises (Edholm et al., 2014; Mohr et al., 2004). These exercises have been found to be appropriate to increase muscle temperature but may fail to induce protective mechanisms to joint loading.

8.5.2 Effects of RWU on isokinetic parameters

In the present study, no significant differences between the RWU and CON condition in all muscle contractions were observed. In contrast, Lovell et al. (2013) observed RWU interventions during half-time interval attenuated H_{ecc} strength reductions. This discrepancy could be explained through differences in participant selection. The participants used in our study were recreationally trained compared to semi-professional soccer players in their study. It might be argued that the type of RWU protocols used in this study (~70% of peak heart rate) could result in some fatigue in our recreationally trained participants. A significantly higher heart rate response was observed during the start (time 60 min) of second half in RWU compared to CON condition (127 vs 97 beats $\cdot$ min^{-1}). Thus, this may compromise the re-warm up effects during the initial stages of second half.

8.5.3 Limitation

Due to the nature of this investigation, the participants' muscle temperature was not measured. Previous studies have consistently observed a reduction in muscle temperature during passive half-time interval and have shown that a RWU protocol such as utilised in this study inhibits such reductions (Lovell et al., 2013; Mohr et al., 2004). This could not be confirmed in our study, as measurement of muscle temperature was not feasible within the already extensive protocol.

8.6 Conclusions

To our knowledge, this was the first study to report the influence of half-time RWU intervention on selected biomechanical and muscle strength related markers of ACL injury risk. Reduced eccentric hamstring strength and muscle imbalances, and a trend towards a more erect hip landing posture, suggested a greater risk of ACL injury during the later stages of match-play when no half-time RWU was implemented. Despite the growing evidence of physical performance improvement after half-time RWU in soccer players, in our study RWU did not offset these observed impairments in markers of ACL injury risk. The efficacy of this intervention towards reducing ACL injury risk therefore remains unknown and deserves further investigation.

Chapter 9

General Discussion

9.1 Introduction

The overall aim of the research described in the present thesis was to investigate the effect of exertions induced by soccer match simulation on biomechanical and muscular markers of ACL injury risk, and to identify needs and opportunities for injury prevention programmes.

Specifically, the objectives across the different studies were (a) to investigate the differences in physiological response between overground and treadmill match simulation, (b) to examine the effects of treadmill versus overground soccer match-play simulation on biomechanical and muscular markers of ACL injury in both male and female soccer players, (c) to investigate the temporal changes in markers of ACL injury risk during soccer match simulation, and (d) to demonstrate the impact of a half-time re-warm up intervention on those temporal changes in biomechanical and muscular markers of ACL injury risk during a soccer match-play simulation. The purpose of this final chapter was to integrate findings from the different experimental studies in the thesis and form an overall conclusion of the research conducted. Generalised recommendations for practical implications will be explored, as well as future research directions.

9.2 Treadmill versus overground match-play simulation

Here the first and second objective of the thesis will be addressed, attempting to reach a general consensus on whether treadmill and overground match-play simulations achieve the same thing or not. To address the first objective of this thesis, the experimental studies detailed in Chapters 3, 4, 5 and 6 demonstrated that in both male and female participants, an overground simulated match-play induced a greater physiological response (higher heart rate and RPE) compared to the treadmill simulation. As overall running velocity was matched between simulations, the findings suggest it was attributed to the high acceleration-deceleration and multidirectional utility movements in the overground match simulation. During soccer matches, up to 36.9% of total distance covered is performed by using utility movements (Thatcher & Batterham, 2004). This has been reported to increase the physiological and metabolic load, as well as muscular fatigue in soccer (Bangsbo, 1994a).

The close similarities between physiological responses observed during the present study and values reported from actual match-play (Bangsbo, 1994a; Krustrup et al., 2006; Mohr et al., 2004; Thatcher & Batterham, 2004; Van Gool et al., 1998), and the ecologically justifiable inclusion of high acceleration-deceleration as well as multidirectional utility movements, justified the use of overground simulations for replicating the demands of soccer, more so than treadmill simulations.

The benefits of overground simulation over treadmill simulation were further supported by observations in Chapters 5 and 6, when addressing the second objective of this thesis. In Chapter 5, an overground simulation was found to induce a higher reduction in H_{ecc} strength compared to the treadmill simulation in males. On the other hand, in Chapter 6 using female soccer players, similar outcomes in reduced H_{ecc} and functional H_{ecc}:Q_{con} ratio were observed. The gender specific response may suggest that for female athletes the treadmill simulation had a relatively similar intensity compared to the overground, and the participants experienced similar muscular demands. Qualitative observation during the test sessions gave an impression that for a number of females the match-play simulations were nearer to their maximal capacity, especially during sprinting which could mean that for these individuals the effect of both simulations may have seen a ceiling effect. In addition, similar reductions in females may also be explained by our lower limb selection. Contrary to males, females have been shown to more likely injure the ACL in their non-dominant limb (Brophy et al., 2010). Whether overground simulation would have a greater impact than treadmill simulation in the non-dominant limb of female participants requires further investigation.

Overall, this study was the first to investigate the influence of treadmill versus overground match-play simulation on biomechanical and muscle strength related markers of ACL injury in male and female soccer players. Our findings support the use of an overground simulation to represent a soccer match exertion rather than a treadmill simulation. Together with the physiological responses observed, the detrimental effects on muscular capacity provided sufficiently compelling evidence that an overground simulation is more suitable for use in further research efforts investigating match-play as a contributing factor to increased ACL injury risk.

9.3 Soccer match-play and its influence on key biomechanical markers of ACL injury risk

Here the third objective of this thesis is addressed. In Chapters 4 and 6 it was demonstrated that 45 min of soccer match simulation does not induce any negative changes in peak knee abduction moments and knee extension angles, in both male and female soccer players. In contrast, other studies have found that high levels of exertion induced increases in peak knee abduction moments (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009), and increased knee extension angles (Chappell et al., 2005; Cortes et al., 2012; Greig, 2009). A first possible explanation for these conflicting results was the belief that an anticipated side cutting manoeuvre is a relatively simple task, and insufficiently challenges the individual. This would leave room for compensatory behaviour that avoids increased joint loading due to match-play. The demands of unanticipated side cutting have been shown to induce greater differences in electromyographic responses (Besier, Lloyd, Cochrane, et al., 2001) and knee mechanics after fatigue (Borotikar et al., 2008) compared to the anticipated side cutting manoeuvre. This explanation was largely refuted, however, since in Chapter 7 we also did not find any increases on knee abduction moments in an unanticipated side cut. On the contrary even, a reduction was noticed in the second half. This unexpected phenomenon will be addressed in further detail below.

Another explanation for the lack of differences, could be that other studies had utilised fatigue protocols involving jump tasks and/or high intensity, short duration (< 10 min) exercises designed to induce a level of volitional exhaustion. These protocols fail to elicit similar physiological and muscular demands to those experienced in soccer match-play, but may have a more dramatic impact on the participant's behaviour and lead to increased joint loading. In our match simulation, there is a fairly even distribution of low and high intensity tasks, and the participants may generally have sufficient recovery to counteract the negative effects of high level of exertion. The activity profile in our soccer match simulations does not include any unexpectedly long sequence of high-intensity activities following each other. During actual soccer match, players have been shown to experience 'temporary fatigue' after performing high intensity running (Mohr et al., 2003), and whether this type of fatigue is the one that induces the greater risk of injuries would definitely deserve further investigation.

Further insights into how the biomechanical markers of ACL injury risk are progressively affected during prolonged intermittent multidirectional simulation were gained in Chapter 7. When participants completed a 90 min multi-directional overground match-play simulation comprising two 45 min halves separated by a 15 min half-time interval, and unanticipated side cutting tasks were observed as an integral part of the 90 min match-play simulation, it was found that match-play induces landing with gradually greater knee and hip extension angles (more extended) during the second half. The more erect landing posture at initial contact suggested a greater risk of ACL injury during the latter stages of match-play and at the start of second half, supporting epidemiological observations of increased injury risk (Ekstrand et al., 2011; Hawkins et al., 2001). This finding suggest that a 45 min match-play simulation was insufficient to induce movement adaptations that reveal changes in biomechanical markers of ACL injury risk. This finding may also suggest that ACL injuries during the first half of match-play are potentially due to muscular imbalance rather than adverse biomechanical hip and knee configurations at impact.

Interestingly though, as mentioned earlier, the peak knee abduction moments were actually found to reduce with match-play. This in itself would be considered a reduction in ACL injury risk, yet against the more extended joint landings (see previous paragraph) and imbalances in muscular capacity (see below), the overall tendency would be towards increased ACL injury risk. Reduced peak knee abduction moments observed in this study may be explained by the fact that participants are male soccer players. Previous studies have suggested that high levels of exertion lead to increased peak knee abduction moments during cutting tasks in females (Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009), yet we believe that our study is the first to do this in males. Differences in injury mechanisms between men and women have been described in the literature, in particular the notion of a frontal plane loading mechanism in women versus a sagittal plane loading mechanism in men (Quatman & Hewett, 2009). Our results may therefore represent sex-specific movement adaptations due to exertion of match-play, i.e. adaptations in men that reduce rather than increase frontal plane loading. Although peak knee abduction moments have been recognised as a predictor of ACL injury in females (Hewett et al, 2005), there remains no conclusive evidence that this variable is meaningful for the role of match-play on risk of ACL injury in side cutting manoeuvres in males. The reduction in peak knee abduction moments may also suggest a compensation strategy adopted by our participant as a protective behaviour to cancel out the negative effect of exertion, but in actual match-play the context and competitive nature may be such that this compensation strategy becomes ineffective. A more comprehensive analysis of our kinematic and kinetic data may reveal the nature of such compensation strategy, but this was beyond the scope of this thesis.

The increases in knee (Chapter 7) and hip (Chapters 7 and 8) extension angles (more extended) at initial contact during side cutting are perhaps the most prominent findings related with markers of ACL injury. Particularly the knee was in a very extended configuration (approximately 13°) at the end of the match simulation. Previous studies found that most of the ACL injuries occurred when the knee extension angle was less than 30° (Cochrane et al., 2007). The match simulation induced a 5° change in knee angle. Although this 5° might not appear to be clinically relevant, we believe it is important when analysing how the knee responds to the demand of exertion induced by soccer match-play.

Overall, the key findings suggest that in male soccer players the sagittal plane mechanisms are likely affected by match-play as opposed to frontal plane mechanisms. This information may provide important practical implications for the development of ACL injury prevention strategies.

9.4 Soccer match-play and its influence on muscle strength imbalances as a marker of ACL injury risk

Chapters 5, 6 and 7 demonstrated that following 45 min or 90 min of match-play simulation, a significant reduction in H_{ecc} strength (averaging 10.4% - 20.1%) and functional $H_{ecc} : Q_{con}$ ratio (averaging 8.1% - 18.4%) with generally no changes in Q_{con} strength was consistently observed in both males and females, supporting other studies (Cohen et al., 2014; Delextrat et al., 2011; Delextrat et al., 2010; Greig, 2008; Small et al., 2010). These findings perhaps were the strongest evidence in support of the detrimental association between match-play and ACL injury risk in soccer players. The functional $H_{ecc} : Q_{con}$ ratio is considered the most representative measure of muscular demands in soccer where the hamstrings are believed to act eccentrically to decelerate the tibia during rapid and powerful concentric knee extensions (Bruckner & Khan, 2012; Sun et al., 2015). The reductions in functional H_{ecc} : Q_{con} ratio are likely attributed to the reductions of H_{ecc} contractions compared to the quadriceps, as the high proportion of type II muscle fibres in the hamstrings are characterised by a lower resistance to fatigue than type I muscle fibres (Garrett et al., 1984). In soccer, H_{ecc} muscle contraction is needed to assist the ACL in stabilizing the knee joint during explosive knee extensions performed when sprinting, jumping, or kicking the ball (Draganich & Vahey, 1990). The observed reduction in H_{ecc} strength with match-play simulation may further impair the muscle's capacity to act as a knee stabilizer, especially when the Q_{con} was not affected and hamstrings are unable to counteract the continued high forces generated by the quadriceps, adding more stress on the ACL (Delextrat et al., 2010).

No detrimental effects on Q_{con} strength were observed following match simulations in Chapters 5, 6 and 7. In addition, Chapter 5 also found no impairments in conventional H_{con} : Q_{con} ratio. Similar findings have been reported in male (Cohen et al., 2014; Delextrat et al., 2010; Greig, 2008; Small et al., 2010) and in female soccer players (Delextrat et al., 2011). In soccer, intense quadriceps concentric contractions are involved at the start of an explosive movement such a jumping, sprinting, changing direction, or when kicking the ball. Within this context, the results suggest that in females, like in males, exertion induced by match-play does not negatively influence the force generating capacity of the quadriceps muscles, and that they are able to perform powerful knee extensions as part of these specific movements at a high intensity throughout match-play.

This research demonstrated a trend towards significant increases over time in Q_{con} angle of peak torque in male players (Chapters 5 and 8) but not in females (Chapter 6). A shift in Q_{con} angle of peak torque in the direction of longer muscle lengths (a more flexed knee) has been widely attributed to the "popping sarcomere hypothesis" (Morgan, 1990). It has also been suggested to potentially cause a significantly greater loss of relative force to occur at shorter muscle lengths compared to optimal or long muscle lengths, as associated with muscle damage from eccentric contractions (Byrne et al., 2001), and may increase susceptibility to injury (Brockett et al., 2001). In addition, in Chapter 8 a shift in H_{ecc} angle of peak torque towards a shorter muscle length would mean that the muscle operating range would be on the descending limb of the length-tension curve (Brughelli & Cronin, 2007), and muscles are more likely to become injured when operating in a more lengthened position (Garrett, 1990). Nevertheless, neither in males nor in females was there strong evidence of a shift in angle of peak torque, and this deserves further attention in future research.

9.5. The impact of half-time RWU on markers of ACL injuries

The fourth objective of this work was to examine the acute effects of an intervention programme during half-time rest interval, specifically designed to reduce the risk of ACL injury. A noteworthy observation from Chapters 4, 5, 6 and 7 was the negative impact on some of the biomechanical and muscle strength imbalance related markers of ACL injury risk after 15 min of passive rest during the half-time interval, or at least no indications of impairments being offset due to passive half-time rest. A reduction in muscle temperature (1.5 – 2.0 °C) observed after the passive half-time interval has been speculated as the primary mechanism to jeopardise half-time recovery (Lovell et al., 2013; Mohr et al., 2004). Re-warm up has been shown to increase muscle temperature, increased nerve conduction rate, and increased contraction velocity (Mohr et al., 2004) which have been shown to increase physical performance during the second half of match-play (Edholm et al., 2014; Lovell et al., 2013). Therefore, this was considered a feasible intervention to reverse some of the observed negative effects on markers of ACL injury risk too. However, in Chapter 8 the main findings revealed that RWU did not offset impairments in markers of ACL injury risk. This discrepancy could be explained through differences in RWU exercises selection and participant selection. The RWU intermittent agility exercises used in our study was adopted from Lovell et al. (2013) and may induce similar changes in increased muscle temperature, but this did not induce specific movement adaptation to reverse negative effects on biomechanical markers of ACL injury. It could be suggested that incorporating exercises that focus on re-activating the relevant musculature rather than simply re-warming may be necessary to have an impact, for example by doing a series of drills which involve key dynamic activities during soccer match (e.g., side cutting, jumping and landing), and possibly augmenting a correct neuromuscular facilitation with feedback on movement execution.

Another explanation for the lack of effect could be that the participants used in our study were recreationally trained. It might be argued that the type of RWU protocols used in this study (70% of peak heart rate) could result in some fatigue in our recreationally trained participants compared to semi-professional (Lovell et al., 2013) and professional soccer players (Edholm et al., 2014), and thus compromise the re-warm up effects during the initial stages of second half and later stage of match-play by inducing further fatigue. It is important to note that our study was only a first attempt to investigate reversal effects of RWU on biomechanical and muscular markers of ACL injury risk, yet further work is required to determine the dose-response characteristics of different RWU intensities, as well as potentially alternative half-time intervention that may well lead to a reversal of detrimental effects from match-play.

9.6 Practical Implications

The findings in this thesis suggest a number of practical implications that could be applied to future assessment of ACL injury risk in soccer players, as well as in the context of prevention of ACL injuries. These are outlined below:

9.6.1 Match-play simulation during screening

The work in this thesis provides compelling evidence that one should perform pre-season and/or injury screening with, where possible, the introduction of overground match-play simulation as part of the screening. This can provide critical information on adaptations to match-play in terms of biomechanical and muscular markers of ACL injury risk.

9.6.2 Interventions focusing on offsetting the negative effect of match-play on biomechanical markers of ACL injury risk

In this thesis there were some biomechanical markers that were negatively affected by soccer match-play simulation, mostly knee extension angles at landing. Therefore, intervention strategies as part of training should focus on these factors. To improve knee extension angles at landing, it has been recently suggested that neuromuscular control training that consists of plyometric and resistance exercises and with addition of a feedback component (verbal or video) can lead to positive improvements in movement execution (Ter Stege, Dallinga, Benjaminse, & Lemmink, 2014). Feedback training is commonly used to change motor control strategies to perform those athletic tasks in which ACL injury frequently occurs (Dai, Herman, Liu, Garrett, & Yu, 2012b). However, these intervention strategies have only shown improvement in females. Further research is still needed to determine which injury prevention programmes can reduce the biomechanical risk factors related to knee extension angles in males.

9.6.3 Interventions focusing on offsetting the negative effect of match-play on muscle strength related markers of ACL injury risk

Reductions in eccentric hamstring strength during match-play simulation have been consistently observed in this work. Performing eccentric hamstring strengthening exercises, and that particularly when in a fatigued state, can promote hamstrings fatigue tolerance (Small, McNaughton, Greig, & Lovell, 2009). This can be implemented by performing these exercises (i.e., Nordic hamstring curls,) at the end of training sessions (during cool-down). Moreover, to maximize the practical application of soccer specific exertions, it has been recommended that these exercises can also be performed after a series of small-sided games (Greig & Siegler, 2009). Performing exercises that specifically strengthen the hamstrings at long lengths, which have previously been describe in Schmitt, Tim, and McHugh (2012), again if possible in a fatigued state, could also help prevent detrimental effects due to match-play.

9.7 Future Research Recommendations

There are several potential areas of future research which have emerged from the studies detailed within the thesis. These are outlined below:

9.7.1 Extending ecological validity to match-play simulation

To replicate a more soccer-specific demand of match-play, future research might consider the inclusion of ball handling skills (e.g., kicking, heading), such as those simulations developed by Bendiksen et al. (2012) or Williams et al. (2010), and with the presence of an opponent. Future studies could also be performed on the usual playing surface (e.g., artificial grass) or wearing soccer specific footwear (e.g., boots, astro turf), as these factors are known to affect biomechanical markers that could influence injury risk (Eils et al., 2004).

9.7.2 More comprehensive evaluation of markers of ACL injury risk

These comprehensive evaluation recommendations are outlined below:

9.7.2.1 Biomechanical markers

The biomechanical observations made were only and limited to the observation of previously identified knee and hip markers of injury risk. Future studies should include trunk and upper body motion as it has been recently shown to influence knee loading during dynamic tasks (Hughes, 2014; Shultz et al., 2012). Furthermore, multi-plane assessment of the ankle angles and moments also could provide greater detail on its relationship to knee loading as has been previously suggested (Boden et al., 2009).

9.7.2.2 Comprehensive statistical approaches

Future studies should include more comprehensive statistical approaches such as Principal Component Analysis or Functional Data Analysis for data exploration (Deluzio et al., 2004), or Statistical Parametric Mapping for hypothesis testing (Pataky, Robinson, & Vanrenterghem, 2013). This would support further interrogation of the movement kinematics and kinetics, and may reveal other effects of match-play simulation, and of preventive interventions.

9.7.2.3 Torque angle profiles

As present study only analysed peak torque and angle at which the peak torque is attained, future studies might consider to include full torque angle profiles of these muscles, which has been recently investigated (Cohen et al., 2014). In addition, future studies could also include a more comprehensive method to identify variations in torque angle profiles by using comprehensive statistical approaches mentioned above.

9.7.3 Electromyographic (EMG) analyses

The present study was unable to determine the cause-and-effect relationship on the observed changes. The implications of the findings would be enhanced with the inclusion of EMG analyses, to further understand the match exertion influence in muscle co-activation which also plays an important role in ACL injury mechanism (Hashemi et al., 2011). Additionally, further enhancement can be made by using advanced statistical approaches in EMG analyses (Robinson, Vanrenterghem, & Pataky, 2015).

9.7.4 Observing various relevant populations

In the present study, the participants comprised of male and female recreationally trained soccer players, competing at amateur level. Future studies would be needed to assess on various levels of participants, including professional, youth, elderly, as well as ACL reconstructed players who are often considered at an increased risk for ACL injuries.

9.7.5 Interventions to offset the negative impacts of match-play and half-time interval

As been suggested in previous reviews (Alentorn-Geli et al., 2014c; Ter Stege et al., 2014), further research in males is needed to identify which injury prevention programmes can reduce the markers of ACL injury risk specifically related to improvement in knee and hip extension angles at landing and eccentric hamstring strength. Findings from this work suggested a high risk of injury during the early stages of the second half following a half-time interval of passive rest. Hence, it would be prudent to further investigate half-time strategies using different interventions as referred to in the practical implications section (see 9.5). Moreover, the efficacy of other long-term injury prevention programmes (e.g., FIFA 11+ warm-up, Santa Monica Prevention Injury Enhance Performance Programme etc.) should also be investigated using similar biomechanical and muscle strength assessments in combination with overground simulated match-play.

9.8 General conclusions

This study provided strong evidence that the functional $H_{ecc}:Q_{con}$ ratio, primarily through reduced eccentric hamstrings strength, may well be an important marker of ACL injury risk as it was consistently reduced by match-play simulations. Match-play simulations do not appear to induce significant changes in peak knee abduction moments, not even in females for which frontal plane injury mechanisms have been previously proposed, which was an unexpected finding against previous evidence in the literature, and deserves further attention. However, reduced knee and hip extension at initial contact was observed in males, suggesting that previously proposed sagittal plane injury mechanisms are more likely to play an increasingly important role later on in match-play in males. A re-warm up intervention did not lead to a reversal of any of these impairments due to match-play simulation, yet through this work we have gained a greater understanding for the development of better screening and injury prevention programmes.

Chapter 10

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Appendices

Appendix 1.

LJMU Lower-Limb and Trunk (LLT) Model

1.1. Anatomical Markers

<u>Trunk</u>

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)

<u>Pelvis</u>

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

<u>Lower limbs</u>

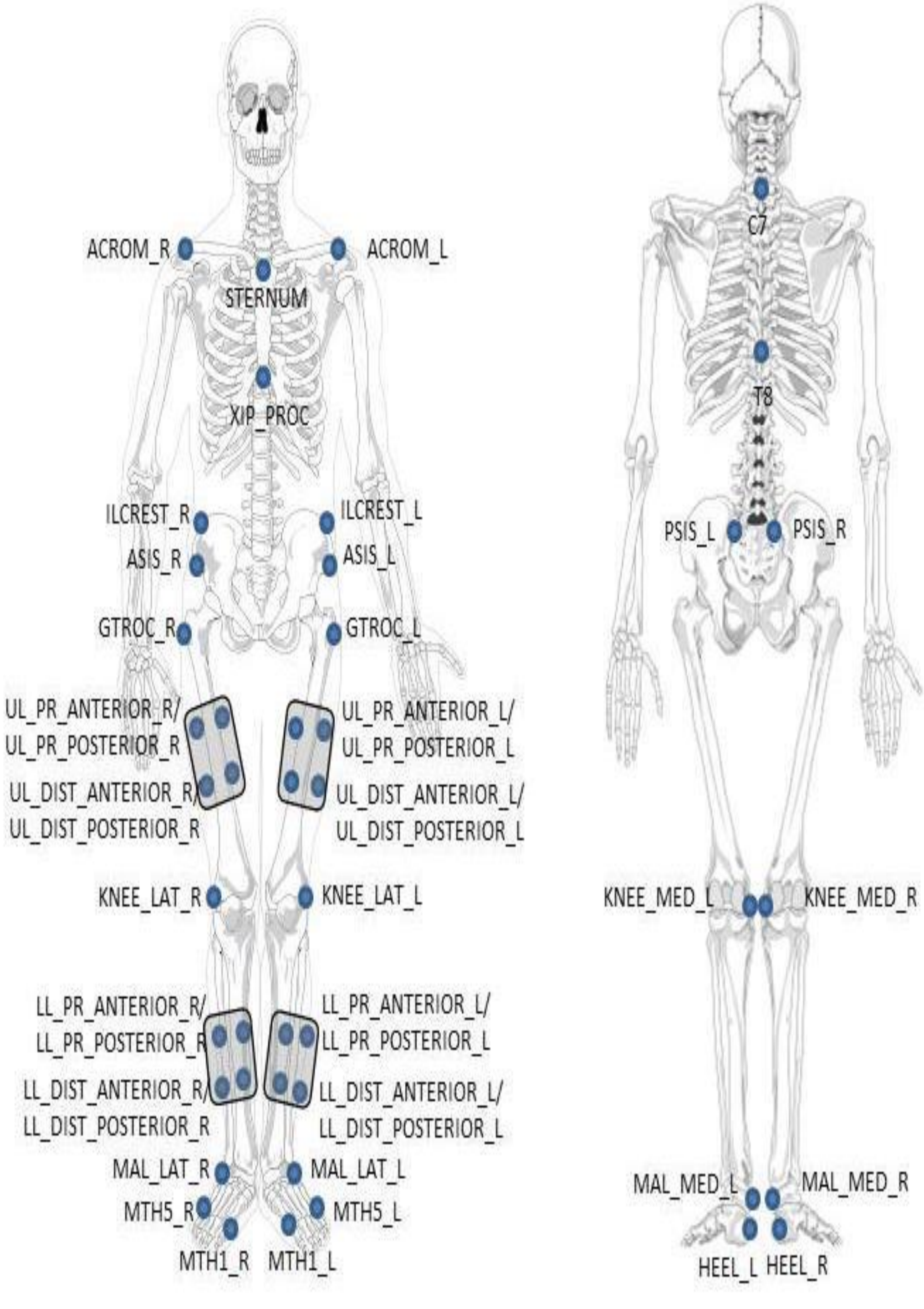
GTROC_L	Greater trochanter left
KNEE_MED_L	Knee medial femoral epicondyle left
KNEE_LAT_L	Knee lateral femoral epicondyle left
MAL_MED_L	Malleolus medial left
MAL_LAT_L	Malleolus lateral left
HEEL_L	Heel left
MTH1_L	Metatarsal head 1 left
MTH5_L	Metatarsal head 5 left
GTROC_R	Greater trochanter right
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

1.2 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

1.3 Physically placed markers



1.4 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

1.5 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

<u>Thighs:</u>

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