Exploring the role of football specific fatigue on dynamic knee stability in elite female youth football players

Abigail Mia Priestley

A thesis submitted to the University of Gloucestershire in accordance with the requirements of the degree of Masters by Research in the Faculty of Applied Sciences.

September 2012

ABSTRACT

Young female athletes have a greater relative risk of sustaining an anterior cruciate ligament injury than their male counterparts (Renstrom et al., 2008) and this injury tends to occur towards the end of a game when fatigue is present. The functional hamstring/quadriceps (FH/Q) ratio describes normal knee function by expressing the hamstrings eccentrically and quadriceps concentrically during knee extension and provides information regarding the competence of the hamstrings to provide adequate dynamic joint stability (Aagaard et el., 1998). It is recognised that both muscular and neuromuscular mechanisms are important aspects in dynamic knee stability, however little research has focused on young female athletes. The aim of this study was to explore the effect of football specific fatigue on muscular and neuromuscular components of dynamic knee stability in elite female youth football players. Participants were 36 females from an FA licensed youth academy (U13= 14; U15=9; U17=13) and all tests were performed before and after a football specific fatigue protocol. Torque was determined in a prone position at three angular velocities (60, 120 and 180°/s) during concentric/concentric and eccentric/eccentric cycles. During the eccentric cycle, electromyography was used to determine the electromechanical delay (EMD) of the biceps femoris, semitendinosus and gastrocnemious muscles. Twenty consecutive sub maximal hops were performed in order to calculate leg stiffness. Mixed Model ANOVA indicated a significant time x angle interaction ($F_{2,34}$=3.914, p=0.030) for FH/Q ratio with post hoc tests indicating that only at 0-10° of knee flexion did the ratio decrease from pre to post fatigue (-14.1%). A significant time x group interaction effect ($F_{2,34}$=4.295, p=0.022) was reported for leg stiffness and indicated that the U13 age group decreased from pre to post fatigue (-4.9%), the U15 remained similar (+1.5%) and the U17 increased (+12.3%). A significant time x group interaction effect ($F_{2,34}$=3.404, p=0.046) was reported for EMD indicating that EMD was significantly longer in the U13 age group and this difference was greater post fatigue. Irrespective of angle and velocity, a significant main effect for time ($F_{1,35}$=10.031, p=0.000) and group ($F_{2,34}$=6.356, p=0.005) were also observed revealing EMD to be longer post fatigue (+58.4%). The findings suggest that muscular functioning is not dramatically impaired following fatigue however impairments to neuromuscular functioning were present in all age groups and may be responsible for the increased relative risk of knee injury in female athletes.

AUTHOR'S DECLARATION PAGE

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas. Any views expressed in the thesis are those of the author and in no way represent those of the University.

Signed ……………………………………………. Date ……………………………….

ACKNOWLEDGEMENTS

Firstly, I would like to say a big thank you to Dr Mark De Ste Croix for his constant support, guidance and time throughout the duration of the project. I appreciate everything he has done for me throughout this year which will not be forgotten. I would like to thank the rest of my supervisory team, Dr Rhodri Lloyd and Dr Jon Oliver for their knowledge, time and support throughout the past year.

I would like to thank Gary, Lorea and Youseff for their help and time spent assisting me with my methodologies; Jasmine, Liz, Felicity and Thea for their assistance in data collection and Stacey for her help with data analysis. I would also like to thank my friends and family for their support throughout the last year and putting up with my constant project talk!

I would like to say a special thank you to all of the players and coaching staff at Bristol Ladies Academy for giving up their time and the amount of effort they put into each and every testing session. Without their commitment and willingness to engage in the research process our understanding of the relative risk of injury in young female players would not have been enhanced.

Finally, I would like to thank The University of Gloucestershire and UEFA for funding this project and providing me with a year full of great experiences.

Thank you.

<u>CONTENTS PAGE</u>

LIST OF TABLES

CHAPTER II – REVIEW OF LITERATURE

CHAPTER III - METHODS

CHAPTER IV - RESULTS

LIST OF FIGURES

CHAPTER II – REVIEW OF LITERATURE

CHAPTER III - METHODS

CHAPTER IV - RESULTS

LIST OF PLATES

CHAPTER II – REVIEW OF LITERATURE

CHAPTER III - METHODS

LIST OF EQUATIONS

CHAPTER III - METHODS

CHAPTER I
INTRODUCTION

Football is one of the most popular sports played worldwide (Vescovi and VanHeest, 2010) with a reported 265,000,000 male and female players regularly competing (FIFA, 2006). This value increased by 10% overall from 2000-2006, with a 54% increase in registered female footballers (FIFA, 2006). It was also reported that The English Football Association (The FA) had 1,485,910 registered players in the country; 97,000 of these being female, further highlighting the fact that the game is as popular as ever in males and females of all ages and continues to develop (FIFA, 2006). April 2011 saw the introduction of the FA Women's Super League which is now the highest level for women to play in the United Kingdom (The FA, 2011). The semi-professional summer league consists of eight teams and was introduced in order to allow female players to earn a good living from the game as well as providing a platform to drive the women's game forward (The FA, 2011). Furthermore, there is a strong player pathway and talent development structure present in women's football with 31 licensed FA Centres of Excellence across England, providing 7-17 year old female players with quality coaching and fixtures on a weekly basis to aid development (The FA, 2011). For all players; regardless of age or sex, a consequence of participation is risk of injury which has a wide range of negative affects upon the player and the club. Therefore the ability to prevent and reduce the incidence of injuries is an important area of research.

The knee is one of the most commonly injured joints during sport accounting for 11-16% of all injuries (Agel et al., 2007, Dick et al., 2007b) with the anterior cruciate ligament (ACL) being one of the more increasingly injured structures (Dargel et al., 2007). Out of all sport related knee injuries 40% are ligament injuries; 46% of these are associated with the ACL and 13% involve the ACL and medial collateral ligament (MCL) in a combined injury (Bollen, 2000). Annually, it is approximated that 80,000 to 250,000 ACL injuries occur in young athletes (Griffin et al., 2006) with 100,000 ACL reconstructions performed annually in the United States (Cheatham and Johnson, 2010). In addition to general injury data, there is a large availability of injury incidence data in male football players however, data on female players is much more limited (Faude et al., 2005).

Information on the injury incidence in youth football is sparse, with only two studies available that focus on female players (Schiff et al., 2010, Lislevand et al., 2011). This is somewhat surprising given evidence that the rate of ACL injury is most prevalent in 14-18 year old girls competing in multiple sprint sports such as basketball, handball and football (Renstrom et al., 2008); which involve many landing and cutting movements, placing them as an at risk population and highlighting the need to understand the mechanisms that are associated with this increased risk.

Many research methods have been employed in order to describe the mechanisms of injury in sport, with non-contact ACL injuries frequently investigated. Landing and cutting movements are often reported as the activities being performed when ACL injury occurred (Renstrom et al., 2008). The angle of the knee has also been identified as an important injury characteristic, with ACL injury often occurring when the leg is close to full extension (Boden et al., 2000). A number of risk factors have been identified for the increased ACL injury in females and are categorised into four distinct categories; environmental, anatomical, hormonal and neuromuscular (Griffin et al., 2006). Neuromuscular factors are often focused on as it is possible to modify them through preventative training (Silvers and Mandelbaum, 2007).

The hamstrings and quadriceps muscles are crucial for knee joint stability and if a muscular strength imbalance exists, the joint is more susceptible to injury (Hughes and Watkins, 2006). Isokinetic dynamometry is frequently used to examine reciprocal muscle group ratios and provide valuable information on knee function, injury risk and knee joint stability (Gerodimos et al., 2003). The functional hamstring/quadriceps (FH/Q) ratio was introduced in order to reflect true knee function and is therefore calculated by assessing the hamstrings eccentrically and quadriceps concentrically during knee extension, or the hamstrings concentrically and quadriceps eccentrically during knee flexion (Aagaard et al., 1998). Previous literature exploring the FH/Q ratio has generally focused on adults, with limited research focusing on the ratio in children. Only one study on children has included girls in the sample (De Ste Croix et al., 2007) and further research is therefore required to explore the effect of age and maturation on the FH/Q ratio in young girls. Research on 12-16 year old male football players has revealed that football specific training produces a decrease in the ratio with age; which reflects that the hamstrings become relatively weaker compared to the quadriceps and places older players with an increased relative risk of injury (Forbes et al., 2009). No research of this kind has been performed on female youth football players, so it is unknown if a similar finding of a decrease in ratio with age and maturation exists.

It has also been identified that efficient neuromuscular control is essential for dynamic joint stability and joint protection (Shultz and Perrin, 1999). Not only the magnitude of this neuromuscular response is valued, but also the speed of the response (De Ste Croix and Deighan, 2012) and it is in question if this muscle activation and joint stiffening occur fast enough to protect the joint. Electromechanical delay (EMD) is often investigated and it is reported and generally accepted that females have a longer delay in reacting to a stimulus than males (Winter and Brookes, 1991, Wojtys et al., 1996, Hewett et al., 2005). As with the FH/Q ratio, very few studies have investigated the EMD during childhood and only one study included girls in the sample (Zhou et al., 1995) therefore the effect of age and maturation on EMD in young girls remains unknown. Additionally, these studies have not examined the EMD of the hamstrings during eccentric muscle actions so it remains to be identified how EMD may change with age and maturation in female youth footballers.

Without adequate stiffness a person may be at risk of injury, thus making stiffness an important factor in preventing ACL injury (Hughes and Watkins, 2006). Available literature has generally focused on adults (Granata et al., 2002, Padua et al., 2005) with limited research conducted on children (Oliver and Smith, 2010, Lloyd et al., 2012). It is suggested that as children mature they become more reliant on feed-forward mechanisms and therefore increase stiffness (Lloyd et al., 2012). However, limited information is available on young girls and is therefore required in order to help describe the associated relative risk of injury and the effects of age and maturation in this population.

It is well recognised that injury is most prevalent in the final stages of sports performance which coincides with when fatigue is present (Small et al., 2010). Therefore, muscular fatigue is often suggested as a risk factor for non-contact ACL injuries (Yu et al., 2002a). Recent studies have indicated that the H/Q ratio is significantly lower at the end of a simulated football specific fatiguing task (Small et al., 2010, Delextrat et al., 2011). However, there is no comparable data available on female youth football players. Similarly, in a study examining fatigue induced using a simulated game on a motorised treadmill, a significant decrease in EMG activity was reported suggesting that in adults', neuromuscular ability to stabilise the knee decreases with fatigue (Rahnama et al., 2006). Furthermore the authors reported additional muscles to be playing an important part in stabilising the knee and suggest a compensatory mechanism was present when fatigued. There is no comparable data available on female youth football players so it is unknown if a similar compensatory mechanism is present. Previous studies on the effect of fatigue on leg stiffness in adults have reported conflicting findings; with reports of an increase (Morin et al., 2011) , a decrease (Dutto and Smith, 2002) and no change post fatigue (Girard et al., 2011). It has therefore been proposed that the fatigue effect on leg stiffness is subject-specific with participants showing an individual response, however there is no comparable data available on the effect of fatigue on the leg stiffness in female youth football players.

There appears to be no studies that have examined the influence of fatigue on the hamstring/quadriceps ratio, electromechanical delay and leg stiffness in young female footballers. It is currently unknown the effect age and maturation has on these outcome measures and how they may influence ACL injury risk and interact with fatigue. Therefore, this study aimed to explore the effect of football specific fatigue on the muscular and neuromuscular components of dynamic knee stability that relate to the relative risk of knee/hamstring injury in elite female youth football players. This was done by focusing on the following research objectives:

1. Explore the effects of a football specific fatiguing task on the muscular and neuromuscular components of dynamic knee stability that relate to the relative risk of knee/hamstring injury in young girls.

2. Investigate whether any age and maturation related differences in key outcome measures exist after football specific fatigue.

3. Explore whether there are muscle specific compensatory mechanisms that contribute to knee stability in a fatigued state.

4. To contribute to our understanding of the influence of football specific fatigue on dynamic knee stability in elite female youth football players in order to help develop pre-habilitation strategies to potentially reduce the relative risk of injury in this population.

CHAPTER II
REVIEW OF LITERATURE

2.1 Injury in football

Due to the nature of competitive sport, football is known to be associated with a relatively high injury risk (Hawkins et al., 2001). Subsequently due to the volume of training and game time players' experience, which generally increase with the standard and age of the player, injuries are frequently observed. Sustaining an injury can have both short and long term consequences for a player as well as the team regardless of the age or level of the player, therefore information regarding the incidence, injury patterns and mechanisms of injury in football is highly valued.

Research on injury incidence in male football players is widely available. The FA Medical Research Programme Audit reported 6030 injuries over two seasons in English male professional players (Hawkins et al., 2001). More recently, Ekstrand et al. (2011) identified 4483 injuries in an injury incidence study by UEFA and stated that the injury incidence was 8 injuries per 1000 hours of exposure. A review of the literature surrounding football injuries by Dvorak and Junge (2000) estimated injury incidence to be between 10-35 injuries per 1000 hours of exposure. Injury surveillance data shows injury incidence to be considerably higher in competition compared to training in both male and female players (Dick et al., 2007a, Dick et al., 2007b), with the lower extremities being the most injured site, specifically the knee (Ostenberg and Roos, 2000, Hawkins et al., 2001). It is also evident that regardless of sex, match injuries increase towards the end of a game (Ostenberg and Roos, 2000, Hawkins et al., 2001) which highlights the potential impact of neuromuscular fatigue on injury risk (Rahnama et al., 2002).

In contrast to the large availability of injury incidence data in male players, epidemiological data on female players is limited (Faude et al., 2005). Hagglund et al. (2009) reported higher injury incidence rates for Swedish professional males compared with females during both training (4.7 versus 3.8 injuries/1000 hours) and match play (28.1 versus 16.1 injuries/1000 hours). Investigations on European female football players report a range of incidence from 4.6/1000 hours

(Jacobson and Tegner, 2007) to 14.3/1000 hours of football (Ostenberg and Roos, 2000) however, overall in adult football, the injury incidence is generally suggested to be greater in males then females (Dvorak and Junge, 2000, Hägglund et al., 2009). The proposed reason for this higher injury incidence in male players is possibly related to the higher velocities and intensity associated with male football (Dvorak and Junge, 2000). Despite this, attention has been drawn to female players as they display a higher risk of injuring the knee than male players, specifically injuring the ACL (Engstrom et al., 1991, Arendt and Dick, 1995, Roos et al., 1995), which also occurs at an earlier age (Roos et al., 1995, Ostenberg and Roos, 2000). Between 70% and 90% of ACL injuries are reported to occur in football in non-contact situations (Hertel et al., 2004) with the incidence in females reported to be 6-8 times greater than their male counterparts competing in the same sport (Hughes and Watkins, 2006). Furthermore, it is suggested that for the same amount of exposure (e.g. 1000 hours of football playing), 14-18 year old females are the most at risk group to sustain a non-contact ACL injury (Renstrom et al., 2008).

In spite of this identification of the increased injury risk to the ACL in young females (Shea et al., 2004, Waldén et al., 2011), information on youth football players, particularly female youth players is sparse (Ekstrand et al., 2011) compared to the abundance of literature surrounding the male dominated game. Rumpf and Cronin (2012) recently completed a review of the literature surrounding injuries in youth football (6-18years) and reported a number of findings. The authors found that the lower extremities were the most injured site, with more injuries occurring in matches compared with training and that low skilled and less experienced players sustained a greater amount of injuries. Furthermore, a high training load with good quality training; including an appropriate warm up related to fewer injuries. Defenders and midfield players were at a greater risk of injury than goal keepers and strikers with female players showing a 2-fold greater risk in comparison with boys. Maturity status was not related to injury risk in youth soccer however, the severity of injury was greater in late maturers. In normal and late maturers the most injured site was the knee compared with the thigh in early maturers. Rumpf and Cronin (2012) reported that total injury incidence is 8.0/1000 hours in 9-12 year-olds, 65.8/1000 hours in

13-15 year-olds and 8.4/1000 hours in 16-18 year olds which suggest there is a significant age effect in the incidence of injuries in youth football. However, the authors did not discuss a possible link between maturational status and injury risk and as the 13-15 age group is typically just after the onset of puberty in females, further research is needed. It is important to note that the review of Rumpf and Cronin (2012) is based on limited well controlled studies and more research is needed that focus on maturational status as well as chronological age to support these initial findings.

There are currently only two available studies that have specifically focused on the injury incidence in female youth football players (Schiff et al., 2010, Lislevand et al., 2011). Lislevand et al. (2011) reported a high injury incidence (93.3/1000h) during a two day tournament in Africa, identifying that most injuries were minor and did not affect the players' ability to compete. However they did identify that players under the age of 16 years had a higher injury risk than those players over 16. Additionally, the lower extremities were the most commonly injured area, accounting for 82% of all injuries. Schiff et al. (2010) reported an injury rate of 4.7/1000 hours of exposure in 12-14 year old female players (n = 80) with injuries occurring more frequently in match play. The authors also identified the ankle (44%), knee (11%) and hip (11%) as the most frequently injured site, with the knee representing the most commonly injured site through overuse (35%).

A recent review of the literature exploring the epidemiology of ACL injury in football from a sex perspective concluded females have a 2-3 times higher ACL injury risk than males (Waldén et al., 2011). Waldén et al. (2011) also stated that injury was more likely to occur during match play and that females were more likely to sustain an ACL injury at a younger age (19 versus 27 years). These findings support various suggestions from the previously mentioned studies on youth and female football players and warrant further investigation in order for practitioners to further understand the age/maturation effect on injury risk in young female athletes. Additionally, there is a need to more clearly understand the mechanisms associated with this incidence rate.

2.2 The Knee Joint and Anterior Cruciate Ligament

The knee; a synovial bicondylar hinge joint, is one of the largest and most complex joints in the body between the condyles of the femur and those of the tibia, with the patella sitting anteriorly (Palastanga and Soames, 2012). The main movements at the knee are flexion and extension which are primarily accomplished by the contraction of the hamstrings or quadriceps respectively (Palastanga and Soames, 2012). The ACL is one of the main ligaments in the knee and together with the surrounding muscles and ligaments, provide joint stability and injury to these ligaments can cause problems to an athlete's career (Grimshaw et al., 2007). The ACL and posterior cruciate ligament (PCL) cross each other inside the knee joint and are named in relation to their tibial attachments (Palastanga et al., 2006).

Shown to tolerate large amounts of bodyweight before rupturing (Woo et al., 1991), the ACL originates from the tibia immediately anterolateral to the anterior tibial spine; passing under the transverse ligament running posteriorly, laterally and proximally before finally inserting into the posterior part of the medial surface of the lateral femoral condyle (Palastanga et al., 2006). The main role of the ACL is to prevent anterior translation of the tibia in relation to the femur and act as a restraint to both internal and external rotation as well as valgus stresses (Dargel et al., 2007, Cooper et al., 2011). The hamstrings are ACL synergists and provide a posterior tibial shear force and therefore limit ACL loading, thus reducing tibial anterior translation and strain on the ACL (Blackburn et al., 2009).

An ACL injury occurs as a result of a lack of stability provided by both the passive and dynamic stabilisers of the knee (Hughes and Watkins, 2006). Non contractile structures of the knee such as the joint capsule, lateral and medial menisci and four extracapsular ligaments; lateral, medial, ACL and PCL provide passive stability to the knee (Hughes and Watkins, 2006). Dynamic stability is provided by the muscles crossing the joint, particularly the hamstrings, quadriceps (Ahmad et al., 2006) and triceps surae (Hughes and Watkins, 2006). Current evidence suggests that the increased incidence of ACL injury in females is as a result of sex differences in the dynamic stabilising structures of the knee (Hughes and Watkins, 2006).

2.3 Incidence of ACL injury

Many studies in sport injury literature refer to incidence rate when addressing injury risk factors, where incidence quantifies the occurrence of new cases of a given injury in a population (Hewett et al., 2007b). Although statistics provide universal information regarding ACL injury risk, they are generally based on the adult population, with the relative risk of ACL injury during childhood yet to be thoroughly explored due to the difficulty in collecting incidence data in this population (De Ste Croix and Deighan, 2012). However, current evidence suggests that in children the knee is the most frequently injured joint, with around 63% of all sports related injuries in 6-12 year olds occurring here (Gallagher et al., 1984).

Early investigations found that high school athletes (14-18 years) had a similar injury pattern to collegiate athletes (DeHaven and Lintner, 1986), with ACL injury incidence higher in female basketball and soccer players than male players (Arendt and Dick, 1995). In contrast, reports that high school soccer players have a higher ligament injury rate than collegiate players are also available (Lindenfeld et al., 1994). Yu et al. (2002b) used data obtained from the American Board of Orthopeadic Surgeons in order to report the age and sex distribution of ACL injuries. The authors established that most ACL injuries occur in the 16-18 year old age group and that males sustain more ACL injuries than females at every age apart from when 15 years old *(Figure 2.1)*. However, a major limitation to this study is that the data only consists of people requiring a surgical reconstruction, therefore failing to account for injuries not resulting in surgery. For that reason, it is possible that this study underestimates the incidence of ACL injury.

Shea et al. (2004) acquired data from a United States insurance company that annually covered over 1 million male and female youth football players in order to analyse ACL injury trends. The general age distribution was similar to Yu (2002) with the highest frequency of injuries occurring in the 14-18 year old age bracket. The pattern with regards to sex however was contrasting, as Shea and collegues (2004) reported that females have almost twice as many ACL injury claims (73 per annum) than males (38 per annum). In every age group from 12 years to 18 years, female injury claims account for a higher proportion of total claims *(Figure 2.2)*.

Again a major limitation to this study is that not all injuries would result in an insurance claim, therefore it is possible that these results underestimate ACL injury incidence.

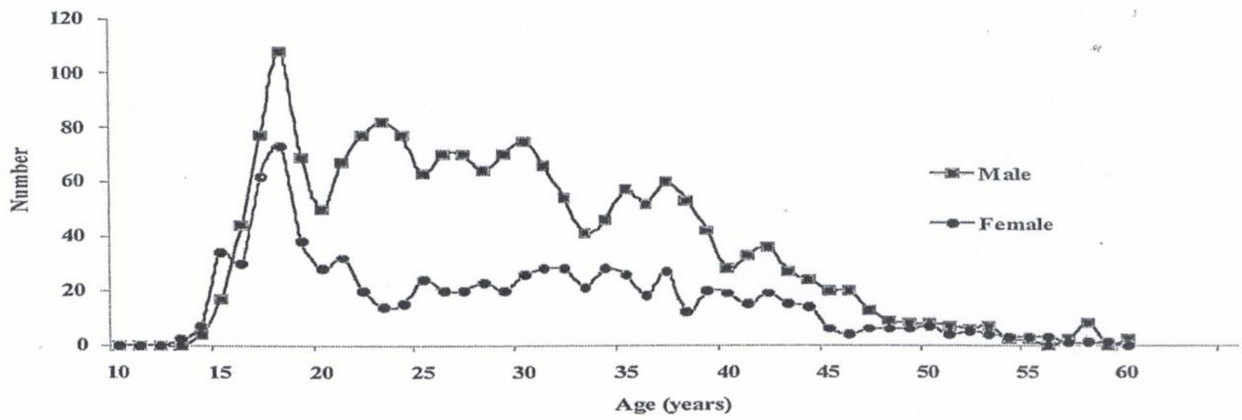


Figure 2.1 Number of ACL reconstructions performed by candidates for certification before the American Board of Orthopedic Surgeons in (Yu et al., 2000b).

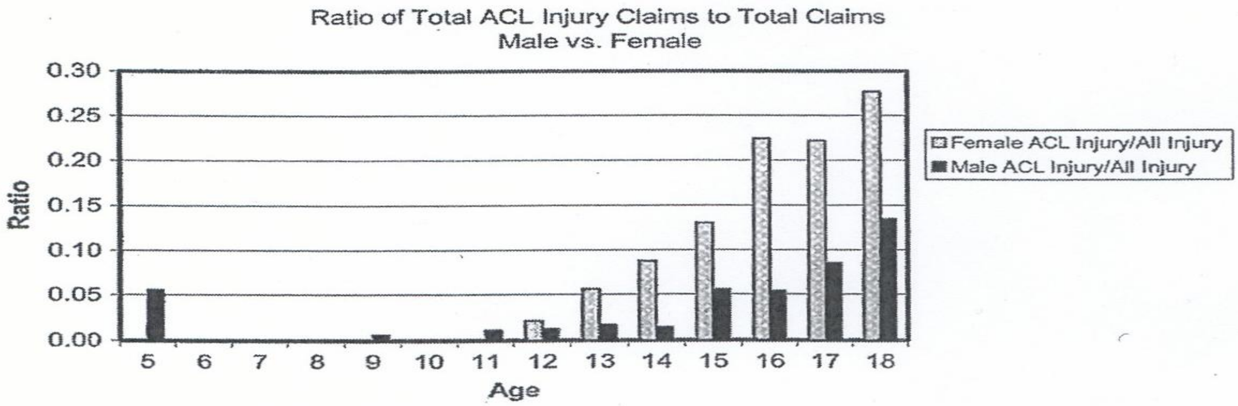


Figure 2.2 Incidence of claims for ACL injury in youth soccer, as a percentage of all claims (Shea et al., 2004).

Similarly, Emery and Weeuwisse's (2010) study on 13-18 year-old male and female football players identified injury rate to increase with age; with the highest injury rate in the eldest age groups. However, they reported no significant sex difference, but noted in females a trend towards a higher risk of ankle and knee injuries than the male players. Despite the small number of studies and limitations to the data, it is consistently shown that there seems to be an increased risk of ACL injury between 13-18 years of age and that this risk is greater in females than males when taking hours of exposure into account.

2.4 Non-contact injury mechanisms

Investigations tend to focus on non-contact ACL injuries because in football between 70% and 90% of ACL injuries are reported to occur in non-contact situations (Hertel et al., 2004). A non-contact ACL injury occurs without any physical contact from an outside source, it is the individual themselves and generally not a result of foul play (Fauno and Wulff Jakobsen, 2006). Therefore, investigating the mechanisms of injury is a vital part of research as it allows an evaluation of any events or causes for injury and as a result develops understanding in this area (Renstrom et al., 2008). Additionally, another concern when returning to sport following an ACL injury is the reinjury rate to the newly reconstructed ACL or to other surrounding structures. Limited data reports a wide range of rerupture rates ranging from 2.3%-13% (Myklebust and Bahr, 2005). With an increased understanding of the mechanisms associated with the why and how these injuries happen, it makes it possible to produce specific interventions in order to try and prevent future sporting injuries (Bahr and Krosshaug, 2005).

A variety of methodologies have made it possible to assess ACL injury mechanisms *(Figure 2.3)*. Interviews with injured players, cadaver studies, video analysis, clinical studies are a few examples of the methodological approaches used to further our knowledge on the mechanisms of ACL injury (Alentorn-Geli et al., 2009). In addition to these methods, recent research has used predictive algorithms to identify those with an increased risk of ACL injury (Myer et al., 2011).

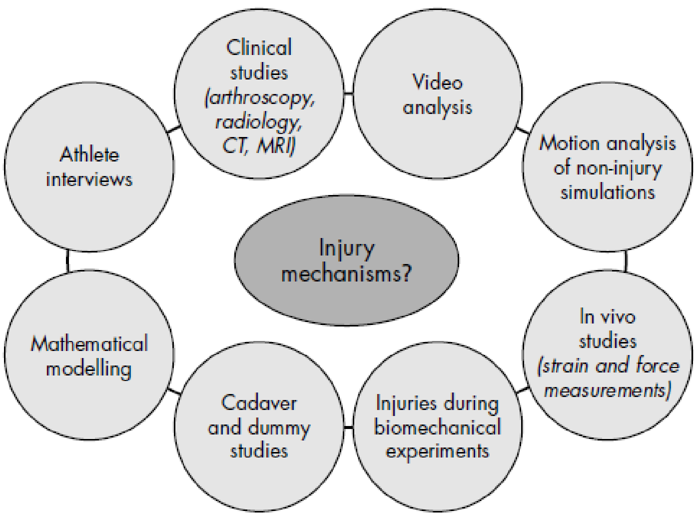


Figure 2.3 Research approaches to describe the mechanisms of injuries in sport (Krosshoug et al., 2005).

Interviews with athletes are a common method used when investigating the mechanisms of an ACL injury. By questioning those who have sustained an injury, it is possible to identify common activities being performed, from data collected through a relatively easy process (Krosshoug et al., 2005). A limitation associated with interviews is the lack of precise definitions of contact and non-contact, whether this means player contact or ground contact (Krosshoug et al., 2005). This could easily confuse the player when reporting back if it is not clarified. As well as this, players might not remember exactly what happened and the situation they were in (Quatman et al., 2010). Video analysis is also a useful method as it allows repeat observations of the events leading up to an injury and can sometimes give a more specific and detailed account when compared with athletes interviews, however it depends on the quality of the footage (Quatman et al., 2010) and it is sometimes difficult to identify the exact moment of injury and if joint positions cause injury or are a result of injury (Shimokochi and Shultz, 2008). Both methods have successfully provided information on both the situation and movement patterns associated with ACL injury with common mechanisms being identified. Non-contact ACL injuries are reported to occur during weight-bearing activities (Boden et al., 2000, Fauno and Wulff Jakobsen, 2006, Ferretti et al., 1992, Olsen et al., 2003), with mechanisms such as landing from a jump (Hewett, 2000); especially with the knee extended or suddenly decelerating the body while running (with or without a direction change) representing the main activities being performed when most injuries occur *(Table 2.1)*. Injured patients clearly stated that upon injury, the injured leg's foot was in contact with the ground (Fauno and Wulff Jakobsen, 2006). Video analysis has also identified cutting and landing situations to be a predominant cause of non-contact ACL injuries (Renstrom et al., 2008), with the knee flexion angle being an important injury characteristic, with injury occurring when the leg is either extended or hyperextended (McNair et al., 1990, Boden et al., 2000).

Table 2.1 Activities observed or reported at the time of Non-contact ACL injuries (Shimokochi and Shultz, 2008).

Reference	Total observed sample	Decelerating from running without changing direction	Decelerating from running with direction change	Jump	Landing	Plant and cut	Unknown
Boden et al. (2000)	81	4	44		32		1
Fauno and Wulff Jakobsen (2006)	105		66		26		13
Ferretti et al. (1992)	84			46	38		
Olsen et al. (2003)	35				16	19	
Total	**305**	**4**	**110**	**46**	**112**	**19**	**14**
Ratio %	**100%**	**1.31%**	**36.07%**	**15.08%**	**36.72%**	**6.23%**	**4.59%**

As well as the above playing situations, specific movements at the joint can occur and are suggested to be involved in the injury mechanisms. These movements include knee valgus, varus, internal rotation, external rotation and anterior translation force, with a combination producing a high strain on the ACL (Alentorn-Geli et al., 2009). Landing in either a varus or valgus also creates a less stable position for the knee (Hewett, 2000). It was suggested by Boden et al. (2000) that the most common kinematic position related to a non-contact ACL injury was when the knee was close to full extension, the foot was planted during deceleration, the tibia was externally rotated and there was a valgus collapse at the knee (Alentorn-Geli et al., 2009). It is therefore suggested that ACL injury occurs when the knee is forced into frontal plane movement with corresponding rotation (Shimokochi and Shultz, 2008, Quatman et al., 2010).

The ACL serves as a restrain to anterior tibio-femoral shear forces. Cadaveric studies have investigated the strain the ACL experiences during various loading patterns and emphasize the importance of anterior shear forces in ACL injury (Renstrom et al., 2008). These studies have shown that the ACL is more vulnerable to excessive anterior loads when the joint is positioned near full extension

(DeMorat et al., 2004). This is due to excessive contraction forces of the quadriceps to decelerate the body at relatively low knee flexion angles (Hewett, 2000) which increase the ACL loading (Shimokochi and Shultz, 2008). This combined with the forces applied through the multiple planes from the valgus/varus and tibial internal/external rotation movement of the player, further loads the ACL and can cause significant anterior tibial translation and cause injury to the ACL (Renstrom et al., 2008, Shimokochi and Shultz, 2008, Alentorn-Geli et al., 2009).

Due to the nature of the game, actions such as cutting, decelerating and landing from a jump are repeatedly performed during training as well as competitive fixtures. Therefore a greater understanding of injury mechanisms and identifying sex-specific risk factors placing young females at risk of sustaining an ACL injury is required.

2.5 Risk factors for ACL injury in females

In order to reduce the number of ACL injuries, especially in female athletes, risk factors must be identified. Understanding injury risk factors is a focal point for researchers and clinicians to help develop effective prevention strategies and interventions to help athletes at risk (Renstrom et al., 2008). Risk factors are generally described as extrinsic and intrinsic; extrinsic or external risk factors are outside of the body, whereas intrinsic or internal risk factors are those within the body (Murphy et al., 2003).

Multiple external and internal risk factors may be associated with ACL injury and these are generally divided into four distinct categories; environmental, anatomical, hormonal and neuromuscular (Silvers and Mandelbaum, 2007, Renstrom et al., 2008, Griffin et al., 2006) with fatigue often suggested as an added risk factor (Yu et al., 2002a). Additionally, risk factors can be categorised as changeable/unchangeable (Minshull, 2004) or modifiable/non-modifiable (Alentorn-Geli et al., 2009) depending on if they can be altered or improved *which* is highlighted in *Figure 2.4.* For both sexes, environmental factors exist and include things such as the sport, footwear and playing surface (Renstrom et al., 2008), however studies tend to focus on the three internal risk factors.

2.5.1 Anatomical and Hormonal risk factors

Various anatomical differences exist between sexes which have been associated with the increased risk of non-contact ACL injury in female athletes (Griffin et al., 2006). The main anatomical difference is that females have an increased quadriceps femoris angle (Q angle), a narrower intercondylar notch and a smaller ACL (Griffin et al., 2006, Silvers and Mandelbaum, 2007), as well as more well know factors such as having less muscle mass and a greater body fat content (Alentorn-Geli et al., 2009). However, there is no definitive evidence that anatomical risk factors are directly related to an increased ACL injury rate in females (Alentorn-Geli et al., 2009) and in addition to this, anatomical factors are generally non-modifiable and therefore there is little or no opportunity for intervention in this area (Hewett, 2000). Hormonal factors have also been investigated with suggestions that estrogen, progesterone and the phase of the menstrual cycle may play a role in the increased ACL injury rates in female athletes (Hewett, 2000), however the results are inconsistent and warrant further investigation (Yu et al., 2002a).

2.5.2 Neuromuscular risk factors

Although it is essential to understand the anatomical and hormonal risk factors associated with ACL injury, they are difficult to modify which therefore leaves neuromuscular risk factors as an interesting topic as they can be improved through integrative neuromuscular training injury (Myer et al., 2011) and proprioceptive preventative training (Silvers and Mandelbaum, 2007). Neuromuscular imbalances have been recognised and related to the underlying ACL injury mechanisms. These are generally referred to as ligament dominance, quadriceps dominance, leg dominance and trunk dominance and can cause dynamic knee instability (Hewett et al., 2010). Furthermore, they are suggested to be responsible for sex differences in ACL injury rates (Hewett et al., 2007a, Yu et al., 2002a).

Ligament dominance is frequently observed in female athletes and the concept is characterised by the lower extremity muscles not adequately absorbing the large ground reaction forces present during sporting maneuvers (Hewett et al., 2010). This inability to control motion results in excessive loading of the joint, especially the ACL as it acts to limit valgus forces, thus making ligament rupture possible (Dugan, 2005). The resulting high ground reaction forces as well as high knee valgus moments and excessive knee valgus motion caused from ligament dominance is one of the key injury mechanism components when the knee collapses into a valgus position (Hewett et al., 2010).

Quadriceps dominance is another neuromuscular control pattern that is associated with ACL injury and refers to the tendency of females to rely on their quadriceps to stabilise the knee joint (Dugan, 2005, Hewett et al., 2010). Females have been shown to recruit the quadriceps over the hamstrings (Dugan, 2005) to produce dynamic knee stability, which increases the strain on the ACL as the quadriceps are an ACL antagonist (Hewett, 2000). Therefore hamstring strength and activation training form the basis of ACL preventative programs (Dugan, 2005). Research has demonstrated that when comparing immature girls and boys with mature girls and boys, boys will significantly increase both hamstring and quadriceps strength whilst females only significantly increase quadriceps strength (Ahmad et al., 2006). This development of quadriceps dominance displayed in young females throughout growth and maturation may put them at an increased risk of ACL injury and highlights the importance of implementing injury prevention programs at a young age. Research has also identified quadriceps dominance in traditionally trained male youth football players (Iga et al., 2009). Currently there is no comparable data on female youth football players, however if this finding is present in conventionally trained females it would further develop quadriceps dominance, placing them with an even greater relative risk of injury.

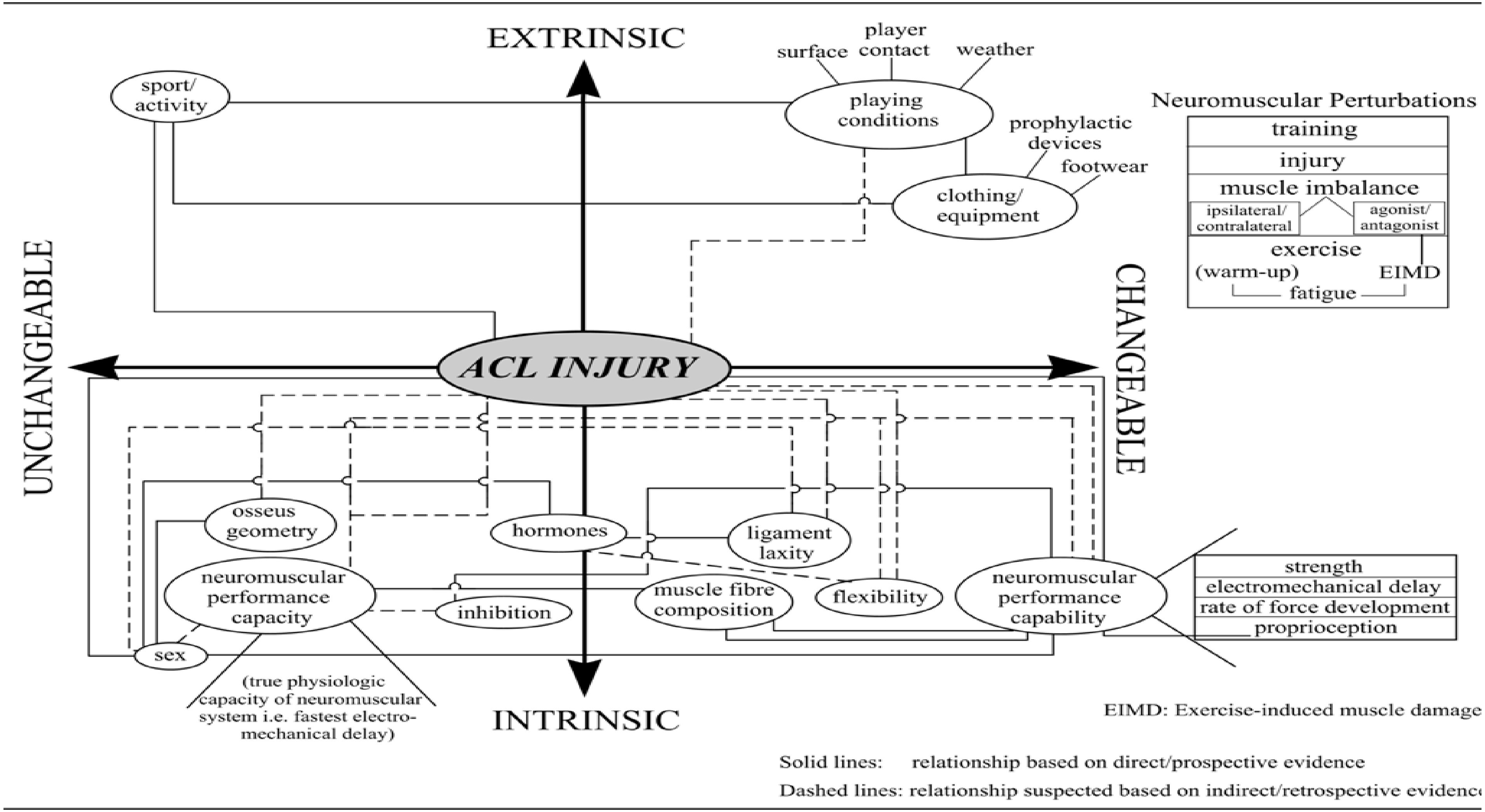


Figure 2.4 ACL injury risk diagram (Minshull, 2004)

Leg dominance is a third type of neuromuscular imbalance between muscular strength and recruitment patterns on opposite limbs (Hewett et al., 2010). This significant side-to-side strength and flexibility deficit tends to be greater in adult females than males (Hewett et al., 2010, Dugan, 2005) and may lead to ACL injury due to the greater stress placed on the dominant knee, or ineffective force absorption in the weaker non dominant knee (Dugan, 2005). Finally, trunk dominance is defined as the inability to control the trunk in three dimensional space and may be related to growth and maturation in females (Hewett et al., 2010). Throughout growth and maturation females increase stature and body mass, resulting in a higher centre of mass which causes difficulty in controlling and balancing the body. In a sporting context, female athletes may display excessive trunk motion and result in medial-lateral torques on the knee (Hewett et al., 2010).

2.5.3 Lower extremity neuromuscular fatigue

It is well recognised in the available literature that injury to the ACL appears to be more prevalent in the latter stages of sporting performance and most likely when muscle fatigue is present (Small et al., 2010). When fatigued, muscles surrounding the knee joint may lose the ability to protect the joint through altered neuromuscular control (Smith et al., 2009) and recruitment patterns (Murphy et al., 2003). Changes in electromyographic activity, joint kinematics and vertical ground reaction force magnitudes may be present as well as changes in lower extremity stiffness during landing. These changes may alter the distribution of forces throughout the joint (Murphy et al., 2003), as well as negatively affect the neuromuscular control of the knee in both males and females, making it more susceptible to injury (Smith et al., 2009). These suggestions add fatigue to the list of potential risk factors for non contact ACL injuries, highlighting the importance of its consideration when studying prevention strategies (Yu et al., 2002a).

Many studies have explored potential risk factors associated with ACL injury, highlighting sex differences that place female athletes with an increased relative risk of sustaining such injury. These sex differences which alter movement patterns, muscle activation and muscle stiffness (Griffin et al., 2006) have led to the focus on neuromuscular preventative programs in order to reduce dynamic knee loading and to help reduce the relative injury risk in females (Shultz, 2008, Hewett, 2000). It is however suggested that ACL injury in female athletes is a multifactorial problem which remains poorly understood (Shultz, 2008) and therefore requires further investigations.

2.6 Role of the hamstrings and quadriceps

The hamstring muscle group consists of the biceps femoris, semitendinosus and semimembranosus, all of which are two joint muscles as they cross the posterior hip and knee joints (Palastanga and Soames, 2012). The quadriceps muscle group consists of the rectus femoris, vastus lateralis, vastus medialis and vastus intermedius, with the rectus femoris originating from the pelvis while the other three muscles originate from the femur (Palastanga and Soames, 2012). Both the hamstring and quadriceps muscles are crucial for knee joint stability playing an important part in several motor abilities such as running and jumping (Bamaç et al., 2008) as well as dynamic movements such as landing and cutting, where reliance is placed on these muscles to provide adequate joint stability and therefore help prevent injuries (Hughes and Watkins, 2006). Muscle actions of the hamstrings (flexors) and quadriceps (extensors) increase joint contact forces and limit shear movement within the tibiofemoral joint. This activity should result in a zero shear load on the tibia, therefore putting minimal strain on the knee ligaments (Hughes and Watkins, 2006). However, if an imbalance exists between the knee extensors and flexors, for example a greater shear load exerted by the quadriceps than the hamstrings, a consequential anteriorly directed shear force may be placed on the tibia, thus increasing ACL strain (Hughes and Watkins, 2006) and therefore making the hamstrings and ACL more susceptible to injury (Holcomb et al., 2007).

Agonist/antagonist muscle groups such as the quadriceps and hamstrings work together in order to control the joint that they cross (Osternig, 2000), which in this case is the knee. When a muscle contracts and causes a movement it is acting as an agonist while another muscle opposes this movement by developing eccentric tension acts as an antagonist (Hall, 2007). The capacity of each muscle to produce adequate force to balance the antagonists and co-contract, is a vital aspect of joint stability (Osternig, 2000).

Changes in muscle length occur with tension development and the resulting muscle force production is described as a concentric or eccentric action (Hall, 2007). A concentric muscle action is when muscle tension is developed and the muscle shortens, with an eccentric muscle action being when muscle tension is developed and the muscle lengthens (Grimshaw et al., 2007). Eccentric tension acts as a braking mechanism in a joint in order to control the speed of a movement and is therefore an important muscular action (Hall, 2007). The importance of the eccentrically co-acting hamstrings in the maintenance of dynamic knee stability during forceful knee extension has been recognised (Osternig, 2000) and therefore forms an important part of preventative training in order to ensure muscular imbalances between the hamstrings and quadriceps are reduced (Kim and Hong, 2011).

2.7 Isokinetic dynamometry

An isokinetic dynamometer *(Plate 2.1)* is a device used to assess isokinetic torque of muscles during various movement patterns and are used extensively in a sport science setting in order to examine neuromuscular performance, as well as within a rehabilitation or medicine setting following injury (Grimshaw, 2006). The device controls the velocity of a movement, keeping it constant and is able to resist the force generated by the participant as well as generate force depending on the mode used (Osternig, 2000).

The primary muscle actions tested are concentric or eccentric and this can be done on the majority of joints within the human body (Grimshaw, 2006). During concentric assessments, the participant is required to accelerate the limb ensuring maximum force is applied against the lever arm throughout the full range of motion. During eccentric assessments, the participant is required to resist the lever arm, again ensuring this is done throughout the entire range of motion. Specifically to the knee joint, isokinetic testing can be used to assess the muscle strength of the hamstrings and quadriceps at a set range of movement and at various angular velocities. From determining the force generated from both muscles in various actions, it allows the calculation of muscle strength ratios (H/Q) which provide information on the functional stability of the knee (Bamaç et al., 2008).

There are various methodological considerations when determining paediatric isokinetic strength. Equipment and protocols should be adapted to enable the appropriate and accurate testing of children, and a familiarisation session should be included in the study design in order to reduce the effect of learning on the test data and ensure valid and reliable data is collected (De Ste Croix et al., 2003). Limited information exists on eccentric strength capabilities in children due to a concern it may predispose them to injury, however if they are adequately instructed and given a sufficient warm up as well as a previous habituation session there is no reason to expect a higher risk of muscle injury (Blimkie and Macauley, 2000, De Ste Croix et al., 2003).

Plate 2.1 Isokinetic Dynamometer

2.8 Hamstring/Quadriceps muscle strength ratios

Reciprocal muscle group ratios are an important part of research due to the fact they provide essential information on muscle balance or imbalance around a joint (Baltzopoulos and Brodie, 1989), however most of the available literature is focused on adults (De Ste Croix and Deighan, 2012). The most frequently reported strength ratio is the hamstring to quadriceps (H:Q) ratio (Holcomb *et al.*, 2007). This is possibly due to the negative implications associated if the quadriceps torque exceeds the hamstrings torque, making the ACL and hamstrings more susceptible to injury (Holcomb *et al.*, 2007). A recent study clearly linked the relative risk of injury to muscular imbalance of the H/Q ratio (Yeung et al., 2009) which further stresses the importance of the H:Q ratio.

2.8.1 Conventional Hamstring/ Quadriceps (CH/Q) ratio

Until recently, the H/Q ratio has generally been conventionally calculated by dividing the maximal concentric knee flexion moment by the maximal concentric knee extension moment (Aagaard et al., 1998). However, as opposing muscles are not capable of simultaneous muscle actions (Holcomb *et al.*, 2007), calculating the CH/Q has been questioned due to its lack of functional relevance. True knee joint movement only allows the hamstrings to act eccentrically while the quadriceps contract concentrically during knee extension or vice versa during knee flexion (Aagaard *et al.*, 1998) which has therefore seen the introduction of a functional ratio.

2.8.2 Functional Hamstring/Quadriceps (FH/Q) ratio

During knee flexion, the hamstrings contract concentrically (H_{CON}) and the quadriceps contract eccentrically (Q_{ECC}), furthermore during knee extension the quadriceps contract concentrically (Q_{CON}) and the hamstrings contract eccentrically (H_{ECC}) (Coombs and Garbutt, 2002). Therefore in order for the H/Q ratio to describe normal knee function (De Ste Croix et al., 2007) and account for the agonist-antagonist relationship, the functional ratio assessing the H_{ECC} and Q_{CON} during knee extension or the H_{CON} and Q_{ECC} during knee flexion is more functionally relevant (Aagaard et al., 1998, De Ste Croix et al., 2007). The FH/Q ratio is therefore calculated by expressing maximal eccentric hamstring moment relative to maximal concentric quadriceps moment at a given angular velocity (Aagaard *et al.*, 1998). The FH/Q ratio identifies the capability of the hamstrings to counteract the quadriceps with a ratio of 1.0 being the recommendation, indicating the competence of the hamstrings to provide adequate dynamic joint stability (Aagaard *et al.*, 1998). However, this value of 1.0 was derived using peak torque (PT) and thus in the middle of the range of movement (De Ste Croix and Deighan, 2012), therefore an adequate ratio closer to full knee extension remains to be determined.

2.9 Effect of knee joint angle on ratio

The importance of joint angle has been highlighted in epidemiological findings, which are in agreement that an ACL rupture is most likely to occur near full knee extension (Renstrom *et al.*, 2008). However, past and present literature have focused investigations on calculating H/Q ratios using PT, which may not accurately represent the functional ratio as the angle of PT occurs in the mid range of joint movement and that the joint angle where PT occurs for eccentric and concentric muscle actions may be different (Forbes et al., 2009). Therefore, when considering the FH/Q ratio it would seem essential to calculate the ratio at various angles approaching full extension in order to establish if a relative injury risk is identifiable through a low ratio.

Recent work by Forbes et al., (2009) has highlighted the issue of using PT to calculate the FH/Q ratio. This study on elite male youth football players (12-18 year-olds) demonstrated that the concentric quadriceps PT occurred at angles from 72-78°, where as the eccentric PT occurred at much lower angle from 31-38°. Therefore a calculation of the FH/Q ratio using PT is being represented by two values that do not reflect a functional movement of the joint as they do not occur at the same angle when the muscles would counteract each other. In addition, it is evident that the joint angle where non-contact ACL injury is likely to occur (0-30°) is not the same angle where PT is generated (30-80° of knee flexion) (De Ste Croix and Deighan, 2012). Based on these findings, it seems apparent that any research on the FH/Q ratio should use angle specific torque values; specifically as the knee approaches full extension, in order to provide functional relevance.

The knee joint angle specific FH/Q ratio has been briefly considered but mainly ignored within the literature, despite its potential in identifying muscle function deficiencies (De Ste Croix and Deighan, 2012). Aagaard et al., (1998) investigated joint angle-specific FH/Q ratio in track athletes, reporting an increase in the ratio with a decrease in joint angle. However, they only used 30°, 40° and 50° of knee flexion; ignoring joint angles lower than 30°. Furthermore, Coombs and Garbutt (2002) calculated angle-specific FH/Q ratios in recreational athletes, including calculations throughout the full 90° range of movement. They also found the ratio increased as the joint moved closer to full extension *(Figure 2.5)*.

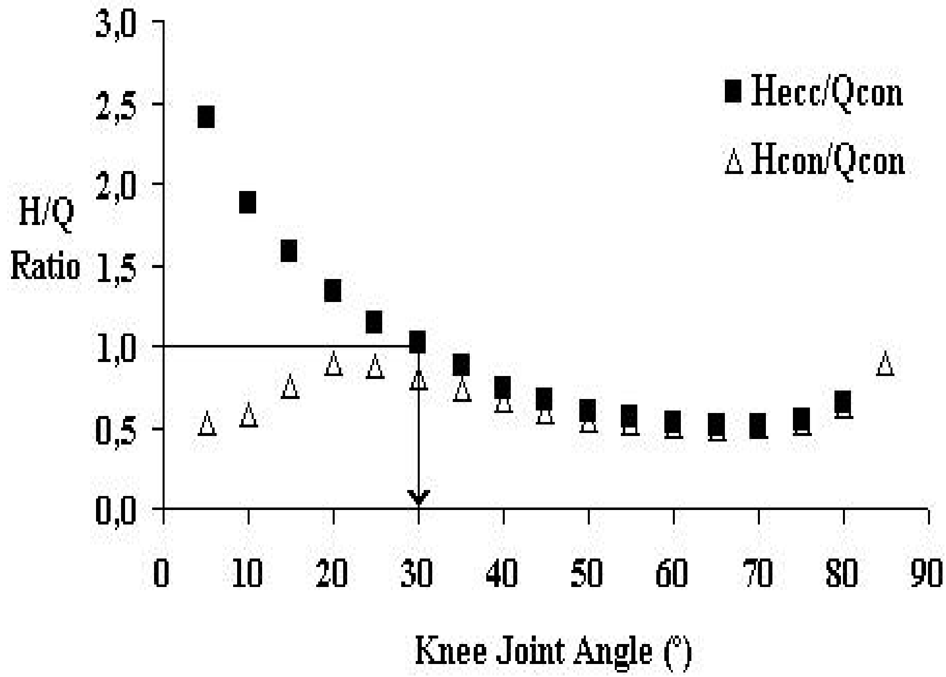


Figure 2.5 Functional hamstring/quadriceps ratio (Hecc/Qcon) as a function of knee joint angle at 60°/s (Coombs and Garbutt, 2002).

One study on pubertal males (13.7 year-olds) calculated the FH/Q ratio at various angular positions (Kellis and Katis, 2007) with the findings corresponding with the adult literature. The FH/Q ratio significantly increased as the knee approached full extension suggesting that young boys have a reduced injury risk during fast movements and when the knee is fully extended, further supporting the importance of using angle-specific calculations. It is possible that this finding would differ in female populations due to the reduced hamstring strength development often displayed throughout the development years in comparison to males (Ahmad et al., 2006). However, this requires future investigation as there is currently a lack of available data on females throughout childhood.

This increase in ratio displayed is due to a decrease in concentric quadriceps strength while eccentric hamstring strength remains relatively constant (Coombs and Garbutt, 2002, Aagaard et al., 1998) and is a reflection of the contractile force to muscle length relationship (Aagaard *et al.*, 1998). At extended knee angles, the hamstrings become close to their optimal length unlike the quadriceps, thus the hamstrings produce a higher force than the compromised quadriceps resulting in a high FH/Q ratio (Aagaard *et al.*, 1998). There are currently no studies available on the FH/Q ratio on females during childhood that have examined the ratio from an angle specific perspective, specifically in the last 30° of knee extension. Future research on high risk populations is therefore needed using angle-specific FH/Q ratio in order to fully understand the functioning of the knee near full extension where knee injury is most prominent (De Ste Croix and Deighan, 2012).

2.10 Effect of angular velocity on ratio

As well as joint angle, epidemiological findings have also identified the importance of considering angular velocity when calculating the FH/Q ratio due to the fact ACL injury is also likely to occur during high velocity movements (Renstrom *et al.*, 2008). As dictated by the force-velocity curve, the FH/Q ratio will increase as angular velocity increases (De Ste Croix et al., 2007). This is due to eccentric torque remaining similar throughout a range of angular velocities, while concentric torque decreases, thus showing an increase in the ratio which occurs regardless of sex (Griffin et al., 1993). Both studies previously mentioned on adults support this by demonstrating that the FH/Q ratio increased as angular velocity increased (Aagaard et al., 1998, Coombs and Garbutt, 2002).

Limited research on the FH/Q ratio throughout childhood is available, with only one study including females in the sample (De Ste Croix et al., 2007). Therefore the effect of angular velocity on the FH/Q ratio in childhood is based on limited studies using a few velocities; however they are in agreement with the adult literature that the FH/Q ratio increases as velocity increases (Gerodimos et al., 2003, Kellis and

Katis, 2007, De Ste Croix et al., 2007). Kellis and Katis (2007) and Gerodimos et al., (2003) both used two angular velocities (60°/s and 180°/s) when investigating the FH/Q ratio in pubertal males. Both authors revealed that the FH/Q ratio was significantly higher at the higher angular velocity (180°/s) suggesting that the knee flexors have a higher capacity to produce maximal moments when near full extension and at increased angular velocities. De Ste Croix et al. (2007) investigated the FH/Q ratio in pre-pubertal children, teenagers and adult male and females and found a significant velocity effect. The authors reported the FH/Q ratio to be higher at faster angular velocities (180°/s) compared with slower angular velocities (30°/s) (De Ste Croix, et al., 2007). This increase at higher velocities was suggested to provide protection against the large anterior tibial translation at high quadriceps forces, through the ability of the hamstrings to significantly contribute to co-contraction.

As only one study has investigated two velocities in young females, it is important that future studies investigate this area, ensuring a range of velocities are used as well as ensuring the FH/Q ratio is calculated using angle specific data. This will increase functionally relevant data for a population at risk of non-contact ACL injury.

2.11 Effect of age and maturation on the H/Q ratio

As previously stated, there is no available research regarding angle-specific FH/Q ratios in children. It is suggested that this gap is due to studies not testing eccentric muscle actions on children due to a fear that eccentric testing may predispose them to a higher risk of muscle injury (De Ste Croix et al., 2003). However, providing the child undergoes a sufficient warm up before testing and previously had a familiarisation session there is no reason to expect a high risk of muscle injury (Blimkie and Macauley, 2000). A few studies have investigated the FH/Q ratio in children, providing valuable information on children across various ages, however only one includes females in the sample (De Ste Croix et al., 2007). These studies can be seen in *Table 2.2* and have generally found significantly higher eccentric compared to concentric strength depending on movement veolcity.

Table 2.2 Paediatric Functional Hamstring/Quadriceps Ratio findings

Author	n	Sex	Age (y)	Velocity (°/s)	Findings
Gerodimos et al. (2003)	180 (30 per age)	M	12-17y	60°/s and 180°/s	No significant age effect Ratio increased as velocity increased
Kellis and Katis (2007)	17	M	13y	60°/s and 180°/s	Ratio increased as knee extends Ratio increased as velocity increased
De Ste Croix, Deighan and Armstrong (2007)	121	M (n=49) F (n=72)	9, 17, 24	30°/s and 180°/s	Ratio increased as velocity increased No significant sex difference Significant age effect (children lower ratio than adults)
Iga et al. (2009)	45	M	15y	60°/s and 250°/s	Decreased ratio in conventionally trained football players compared with resistance trained
Forbes et al. (2009)	157	M	11-18y	60°/s	Significant age effect (lower ratio in 18 y olds)

Gerodimos et al. (2003) investigated both CH/Q and FH/Q ratios in young male basketball players and reported no significant effect of age on either the conventional or functional ratio. From this they suggested young basketball players develop both flexor and extensor torque throughout the developing years resulting in this non-significant effect of age on the ratio. However, conflicting studies are available that report a significant age effect on FH/Q ratio in youth footballers as well as non trained children (De Ste Croix et al., 2007, Forbes et al., 2009).

Conflicting data are available and De Ste Croix et al. (2007) found a significant age effect in the FH/Q ratio. Unlike Gerodimos et al. (2003), the study of De Ste Croix et al. (2007) used an extended hip position, which is functionally relevant as it reflects the body position in sporting activity, and tested concentric cycles before eccentric cycles. De Ste Croix et al. (2007) reported a significantly lower ratio (0.97) in 9-10 year olds at 180°/s than both teenagers (1.23) and adults (1.19), concluding that the low ratio in prepubertal children may be due to an inability to recruit their entire motor unit pool when performing eccentric actions. Consequently, this may be in order to protect their immature musculoskeletal systems (De Ste Croix and Deighan, 2012). As this is the only study on young females further research is necessary to explore this age effect, ensuring a functionally relevant hip position is used as well as performing concentric actions before eccentric in order to rule out the possibility of an increase in concentric torque if performed last (Mohtadi et al., 1990, Hildebrand et al., 1994).

Forbes et al. (2009) conducted a large cross-sectional study on elite male footballers, aged from 12-16 years which conflicts with the findings of Gerodimos et al. (2003) as they reported a significant age effect on the torque profiles collected. The FH/Q ratio was significantly lower in the U18 age group players (0.84) compared with the U12's (1.01). This was due to a greater increase in the torque of the concentric quadriceps compared with that of the eccentric hamstrings. Although these findings are opposite to that of De Ste Croix et al. (2007), it is suggested that sport specific training; in particular a limited focus on eccentric hamstring training in youth football maybe responsible for the conflicting findings. Recent work by Iga et al. (2009) support this and reported a training effect in youth footballers. Players who followed a conventional training schedule which focussed on common technical and tatical skills had a significantly lower ratio compared with players who follow a resistance training schedule focusing on lower-body resistance exercises (Iga et al., 2009). These findings suggest that conventional training asymmetrically strengthens the muscles about the knee, altering balance and thus producing a quadriceps dominance by players. The author concluded that an introduction of a resistance training session may help to ensure lower limb muscle balance (Iga et al., 2009). A major limitation of this study is that the authors did not followed the method of calculating the FH/Q ratio as described by Aagaard et al. (1998) as they used eccentric torque data from a different angular velocity (123.8°/s) to the concentric torque data (61.9 and 247.5°/s) therefore not replicating a functional knee action. No comparable research has been performed on female youth football players however, if this finding is similar for conventionally trained females it would further increase the quadriceps dominance theory and place this population at an even greater relative risk of knee injury, therefore highlighting the need for appropriate training intervention and future research on this population.

Ahmad et al. (2006) investigated maturity and sex differences on different variables including hamsting and quadriceps strength in order to determine when the most appropriate time to introduce an ACL injury prevention program was in youth footballers. They reported significant effects of sex and maturity on quadriceps and hamstring strength *(Figure 2.6).* With maturity, there was a significant increase in both hamstring and quadriceps strength in boys and girls. However, boys developed hamstring strength to a greater extent than females. The authors concluded that girls after menarche increased their quadriceps strength greater than their hamstring strength which may put them at risk of ACL injury.

As there are limited studies available throughout childhood using a FH/Q ratio and only one of these using females, it leaves scope for future investigation in this area. It is essential to understand the functioning of the knee in young females as they are at an increased relative risk of injury. Further investigations should ensure a functionally sound method is followed using angle specific averages to calculate the ratio to fully understand the events occuring withing the joint, especially at the point where knee injury is most likely to occur (0-30° of full knee extension) (De Ste Croix and Deighan, 2012). Furthermore, children need to be introduced to appropriate training as soon as possible in order to develop motor skills and aid muscle strength development.

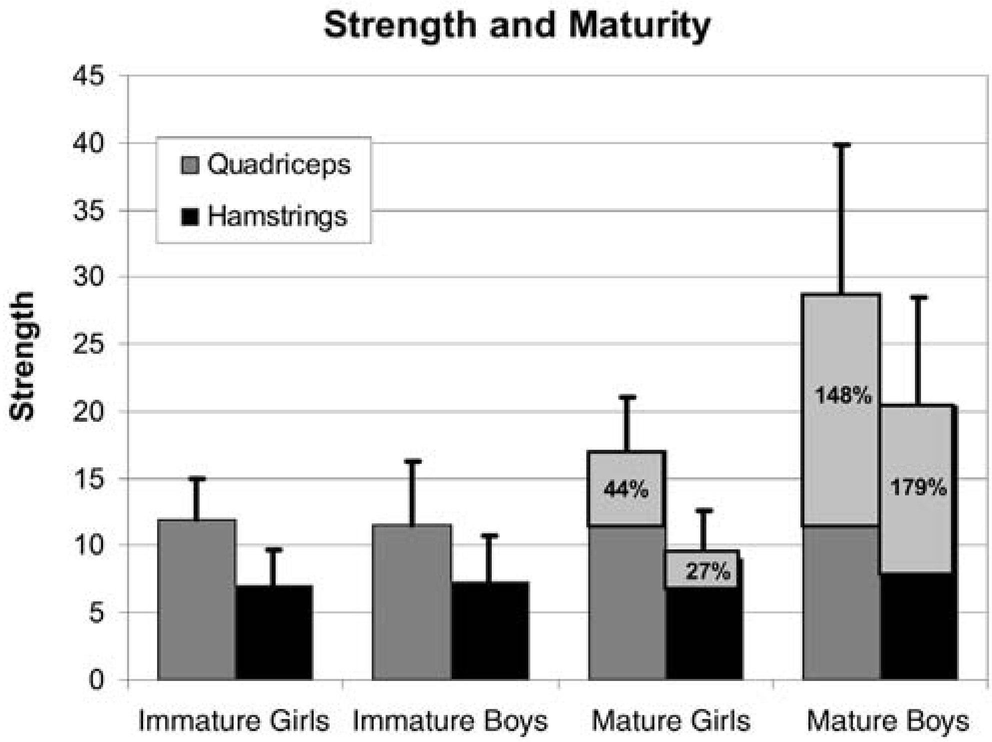


Figure 2.6 Quadriceps and hamstring strength for immature and mature girls and boys (Ahmad et al., 2006).

2.12 Electromyography

Electromyography is a technique used that identifies, amplifies and records the electrical activity of a muscle (Broer and Houtz, 1967) and has been established as an important tool when investigating muscle activation and co-ordination (Rahnama et al., 2006). The use of EMG is widespread in many disciplines but specifically to sports science it is a useful evaluation tool used in relation to biomechanics, movement analysis, strength training and rehabilitation (Konrad, 2005).

Surface electrodes are most frequently used due to the relatively easy and non-invasive application making them convenient (Basmajian and De Luca, 1967). A limitation of surface electrodes is that only superficial muscles can be palpated and therefore assessed (Basmajian and De Luca, 1967), however surface EMG is seen as a reliable measure of the activity in surface muscles (Ghori et al., 1995).

The quality of an EMG measurement relies on appropriate skin preparation as well as accurate electrode positioning (Konrad, 2005). The skin should be cleansed in order to reduce the impedance at the electrode-skin barrier (Gleeson, 2001) which can simply be done using alcohol wipes (Konrad, 2005). More importantly, is the accurate placement of the electrodes on the desired muscles in which a number of steps should be taken in order to ensure a good reading (Broer and Houtz, 1967, Konrad, 2005). Elecrodes should be placed over the most dominent belly of the muscle in parralel to the muscle fibres, with an inter electrode distance no less than 2cm (Broer and Houtz, 1967, Konrad, 2005) The placement of the electrode should remain on the active muscle when it shortens and avoid the motor point regions of the muscle (Konrad, 2005). In additon to this a reference electrode should be placed on a joint or bony area (Konrad, 2005). Correct placement can be checked through a baseline measurment reading ensuring that noise is minimal to allow a clean recording when testing. Basic information such as whether a muscle is active or at rest can be derived from using EMG as a methodology, with the timing of this muscular activity being highly valued (Shultz and Perrin, 1999). Reaction time, electromechanical delay (EMD) and muscle firing patterns have been investigated in response to a stimulus and may be important neuromuscular characteristics in providing adequate dynamic knee stability (Shultz and Perrin, 1999).

2.13 Neuromuscular control and knee stability

It is widely accepted that efficient neuromuscular control is essential to dynamic joint stability and protection (Shultz and Perrin, 1999). Neuromuscular imbalances can be described as muscle strength or activation patterns that lead to an increased load on the joint (Myer et al., 2004). The hamstrings, (ACL synergists), have been identified as important in maintaining the stability of the joint and therefore their activation and co-contraction is often of great interest to researchers (Shultz and Perrin, 1999). Not only the amplitude of this neuromuscular response is valued, but also the speed of the response which is considered vital to ACL protection (De Ste Croix and Deighan, 2012).

Dynamic neuromuscular restrains to the lower extremity joint motion include both feed-forward and feedback motor control loops (Hewett et al., 2005, Ford et al., 2011). Feed-forward neuromuscular control mechanisms are developed through previous repeated movement patterns and activate muscles surrounding the joint before any excessive loading (Ford et al., 2011). This activation allows force absorption and consequently decreases stress on the ligaments (Hewett et al., 2005). Feedback or reactive motor control strategies alter muscle activation in response to situations/a stimulus that load the lower extremity joints such as the knee (Hewett et al., 2005). This EMD which are inherent mechanisms of feedback may limit the effectiveness of muscular joint protection during dynamic movements (Ford et al., 2011). Both mechanisms are important in adults and children, as is appropriate neuromuscular training which can assist the development of both feed-forward and feedback mechanisms in order to increase knee protection (Hewett et al., 2005).

2.13.1 Knee muscle activation

It is not just muscular activation that forms an important part of sports performance, it is the speed of this activation and joint stiffening that is vital to protect the joint from the large forces applied (De Ste Croix and Deighan, 2012). Studies investigating the age and sex associated changes in knee muscle activation during landing and pivoting tasks are available, however this information throughout childhood is sparse. Russell et al. (2007) investigated knee muscle activation during landings in children and adults by determining co-contraction ratios (CCR) of the quadriceps and the hamstrings. Significant age differences were reported, indicating that regardless of sex, adults pre-activated their hamstrings to a greater extent than children before landing. These results propose that the feed-forward mechanism is more developed in adults compared with children (De Ste Croix and Deighan, 2012). This is supported by the work of Lazaridis et al. (2010) who reported a higher and longer pre-activation of the gastrocnemious muscle in adult males in comparison to pre-pubertal boys. Similar results are also reported in a study by Lloyd et al. (2012) who reported pre-activation and short latency activation to increase with maturity when investigation stretch-shortening cycle activities in male youths.

2.13.2 Electromechanical delay

EMD is classified as a characteristic of neuromuscular function (Blackburn et al., 2009) and can be defined as the latency between the onset of electrical activity in the muscle and the onset of force generation by that muscles contraction (Yavuz et al., 2010). One method for calculating EMD was proposed by Zhou et al. (1995) in which the onset of electrical activity was taken as a +15 μV deviation from a baseline measurement to the onset of force production assumed as 9.6Nm. Adult data suggests that EMD can vary between 30-50ms up to as much as a few hundred milliseconds depending on the muscle and muscle activity examined and movement velocity (Shultz and Perrin, 1999). It has been demonstrated that adult females appear to display a longer latency period between preparatory and reactive muscle activation than their male counterparts (Winter & Brookes 1991; Wojtys *et al*., 1996). This increased electromechanical delay (EMD), may be associated with uncontrolled development of forces of sufficient magnitude to cause damage to ligaments during sustained and repeated movements (Winter & Brookes, 1991), therefore implicating EMD as a possible risk factor for knee injury in adults.

Research comparing the sex differences of the hamstrings during eccentric actions in adults reported no significant sex differences (Blackburn et al., 2009). However, in contrast to these findings, available data for other muscle groups show a significant sex difference with males having a quicker activation than females, thus a shorter EMD (Bell and Jacobs, 1986). Thus, concluding that differences in muscle strength between sexes may, in part be due to differences in EMD (Bell and Jacobs, 1986). In spite of this, very few studies have investigated EMD during childhood with only one longitudinal study.

Grosset et al. (2010) investigated ankle stiffness and EMD of the triceps surae in healthy children and children suffering with a hip disorder (Legg-Calve-Perthes disease). They reported a greater EMD in the children with the hip disorder compared with the healthy children, although this was based on a small sample of six children. Research investigating neurological adaptations in endurance trained men and adults during isometric elbow and knee flexion and extension (Cohen et al., 2010) also found a significantly longer EMD in young children (aged 9-12 years-old) compared to adults (65ms versus 57ms). There was however no significant difference between the endurance trained and untrained children, signifying that level of training status does not have an effect on the EMD in 9-12 year old children.

Similarly, Falk et al. (2009) reported a significantly longer EMD in pre-pubertal boys compared with adult males (76ms versus 48ms) when investigating child-adult differences in muscle strength and activation patterns during isometric elbow flexion and extension. Zhou et al. (1995) also found a significantly longer EMD in 8-12 year olds (61ms for boys; 58ms for girls) when compared against 13-16 year olds (44ms for boys; 47ms for girls) and adults (40ms for males; 46ms for females). These differences in muscle activation such as excitation-contraction coupling, muscle fibre conduction velocity and muscle-tendon stiffness have all been associated with longer EMD shown in children (Cohen et al., 2010), however further investigation is required throughout childhood and including females in the sample.

None of the above studies have examined the EMD of the hamstrings during eccentric muscle actions; especially at different joint angle, therefore whether EMD accounts for the greater relative risk of non-contact ACL injury in girls remains unclear, warranting future investigations focusing on EMD throughout childhood during eccentric muscle actions.

2.14 Leg stiffness

The ability of muscles to resist movement by maintaining a particular joint angle within the tibiofemoral joint refers to muscle stiffness (Hughes and Watkins, 2006). The term *stiffness,* is used to describe the force response that results from and also resists mechanical stress (Padua et al., 2005). Without adequate active muscle stiffness, a person maybe at risk of injury, hence muscle stiffness is an important factor in preventing ACL injury (Hughes and Watkins, 2006).

Furthermore, high levels of leg stiffness may result in possible bone injuries while low levels are often associated with soft tissue injuries (Hobara et al., 2008).

Understanding leg and joint stiffness provides those in the field of sports physiology and biomechanics with important information which could be useful when considering performance as well as injury prevention (Hobara et al., 2008). Therefore, it is important to understand the mechanisms in controlling leg stiffness and its relationship to the stretch-shortening cycle (SSC). The SSC is a commonly used muscle action in everyday human movement patterns (Kubo et al., 2007) such as walking, running and hopping (Nicol and Avela, 2006). Muscle actions during rebounding activities classified as SSC must consist of pre-activation before ground contact, a fast eccentric action followed by an immediate and rapid transition from the eccentric to concentric phase (Lloyd et al., 2012). This mechanism of stretching the active muscle before the shortening phase of a movement allows for elastic energy to be stored resulting in a greater force output than from an isolated concentric only movement (Kuitunen et al., 2002). Effective use of elastic energy during SSC muscle actions involves relatively high stiffness in order to allow sufficient absorption of high impact forces (Kuitunen et al., 2002). The SSC is often represented as leg stiffness (Lloyd et al., 2012) with control of stiffness being a function of both feed-forward and feedback mechanisms (Wilson and Flanagan, 2008). Padua et al. (2005, 2006) highlighted various biomechanical parameters that control leg stiffness such as; muscle activation and force, reflex contribution, antagonist muscle co-activation, lower extremity kinematics during ground contact and stiffness properties of the muscle and joint complex. It is therefore the measurement of all of these components that enables investigators to determine the ability of an individual to perform SSC functions.

Lower limb stiffness is often assessed through hopping, jumping and running protocols based in human performance laboratories (Laffaye et al., 2005, Dalleau et al., 2004) as they are highly functional loading conditions (Padua et al., 2005). Traditionally, these protocols allow stiffness to be calculated by utilising the properties of the spring-mass model measured through use of a force platform (Granata et al., 2002). A recent study proposed a field based protocol using mobile contact mats that allowed valid measurement of leg stiffness from data collected on ground contact times, flight times and body mass in adults (Dalleau et al., 2004). This method has since been deemed reliable in using sub maximal hopping to measure leg stiffness in paediactric populations (Lloyd et al., 2009). It is however important to note that when investigating differences in paediactric leg stiffness, a normalisation procedure is used to account for growth and maturation by determining data relative to both body mass and leg length (McMahon and Cheng, 1990).

Leg stiffness is often investigated in relation to performance, as it is suggested to have a major effect on various athletic variables such as the rate of force development, sprint kinematics and elastic energy storage and utilization (Brughelli and Cronin, 2008). There is a strong relationship between the amount of stiffness, force output and velocity, therefore a greater amount of stiffness is seen to increase each variable (Wilson and Flanagan, 2008). Butler et al. (2003) listed various aspects of performance which are influenced by leg stiffness. The authors reported an increase in lower extremity stiffness with an increased hopping frequency and when landing from an increased height (Butler et al., 2003). Additionally, when considered in relation to running, an increase in lower extremity stiffness was present with; an increased running velocity, a decreased stride length and a decrease in energy requirement (Butler et al., 2003).

Available literature relating to leg stiffness has generally focused on adults (Oliver and Smith, 2010) with studies available looking at the differences between males and females. Research by Grantana et al. (2002) has shown leg stiffness to be significantly greater in males than females in two footed hopping. On the other hand, Padua et al. (2005) looked at sex differences in a two foot hopping task, finding a significant difference in leg stiffness with females demonstrating lower levels. However, once normalized for body mass this difference disappeared. Nevertheless; they suggested that the muscle activation patterns differed in that females showed increased quadriceps activity compared with males. Although findings suggest females exhibit less muscular protection through leg stiffness, whether this accounts for the greater incidence of ACL injury requires further investigation over a range of ages (Hughes and Watkins, 2006).

Less is known about the development of neural control and leg stiffness in children as research in this area is particularly sparse. Lambertz et al. (2003) and Grosset et al. (2007) found stiffness increased with age but remained lower than adults when investigating the development and control of muscle stiffness throughout childhood (7-11years). They suggested factors which influence growth such as intrafusal fibre development and reflex control mechanisms for this increase. Similarly, Lebiedowska and Fisk (1999) found stiffness of the knee increased with age in girls and boys and it is suggested that stiffness increased as a function of growth and maturation rather than age *per se (Blazevich et al., 2012)*. These studies however, used an external stimulus in their measurement procedures so therefore may not represent natural SSC actions, which occur through running and jumping activities (Lloyd et al., 2012, Oliver and Smith, 2010).

Recent work by Oliver and Smith (2010) reported at a self selected preferred frequency, men hopped significantly faster with a greater amount of leg stiffness than boys (11-12years). When hopping at a slow frequency (1.5Hz) the men and boys displayed similar control strategies, however at a faster frequency of 3.0Hz the men displayed shorter contact times and a greater measure of leg stiffness. The authors conclude at faster frequencies men are able to increase feed-forward and reflex muscle activity to hop with a greater amount of relative stiffness than the boys. These findings are supported by Lloyd et al. (2012) who investigated age-related differences in the neural regulation of SSC activities in male youths (9, 12 and 15years) during hopping. They reported greater leg stiffness in the 15 year olds than in both the younger age groups. The results suggest that as children mature they become reliant on feed-forward mechanism and short latency stretch reflexes to control greater levels of leg stiffness when hopping.

There is an urgent need for more studies investigating the role of feed-forward mechanisms in the dynamic control of knee stability for injury prevention in children, specifically girls. Understanding how this mechanism differs between age and maturational groups throughout childhood and puberty may help in the design of appropriate pre-habilitation strategies in female youth football.

2.15 Effect of fatigue on dynamic knee stability

As muscles contribute to joint stability (Alentorn-Geli et al., 2009) muscular fatigue is often suggested as a risk factor for non-contact ACL injuries (Yu et al., 2002a). Muscular fatigue can be defined as a reduction in the maximal force exerted by a muscle or a muscle group due to central and/or peripheral mechanisms (Camarda and Denadai, 2011). After fatiguing exercise, alterations to biomechanical and neuromuscular factors associated with an increased injury risk such as; muscle activation patterns, co-activation, kinematics and kinetics and stiffness properties can occur (Padua et al., 2006). Furthermore, it has been well recognised that injury is most paramount in the final stages of sports performance which coincides with when muscle fatigue is present (Small et al., 2010).

2.15.1 Muscular fatigue in childhood

Current evidence suggests that children fatigue at a slower rate than adults during one or several high intensity exercise bouts (Ratel et al., 2006, De Ste Croix et al., 2009). There are a number of proposed mechanisms for this ability in children to maintain force output with a thorough explanation in a review by Ratel et al. (2006), where the authors conclude these mechanisms are most likely related to the different muscle characteristics of children compared to adults. A recent study by De Ste Croix et al. (2009) exploring the age and sex associated differences in isokinetic knee muscle endurance between young children and adults reported children to maintain force output to a greater extent than adults and therefore resist fatigue. This study also reported that there were no sex differences in fatigue resistance between males and females or girls and boys. Further investigation is required as data is limited and does not use a range of ages throughout childhood and there is no available data on the effect of eccentric fatigue on torque production during childhood (De Ste Croix and Deighan, 2012).

2.15.2 Effect of fatigue on FH/Q ratio

Data on the effects of muscle fatigue on the FH/Q ratio in adults is sparse and no studies appear to calculate the FH/Q ratio using a more functional angle specific average after a fatiguing task (De Ste Croix and Deighan, 2012). Knowledge on the effects of fatigue on concentric and eccentric muscle actions is that eccentric actions produce less fatigue, so are therefore more fatigue resistant than concentric muscle actions (Roig et al., 2009). With this in mind, in a fatigued state the FH/Q ratio should therefore increase reflecting a more stable knee. However, a number of studies on male (Small et al., 2010, Greig, 2008) and female (Delextrat et al., 2011) football players provide results that disagree with this concept.

Small et al. (2010) explored the effects of multidirectional football-specific fatigue on markers of hamstring strength. They reported that eccentric hamstring strength and the FH/Q ratio significantly decreased at the end of each half of a football match. A decrease in eccentric muscle strength was also reported by Greig and Siegler (2009). In support of this, a recent study on amateur female football players reported the FH/Q ratio decreased in both legs following a simulated soccer match (Delextrat et al., 2011). This is the only known study assessing the effects of a simulated football test on the FH/Q ratio in female players but supports the findings on male players and suggests changes in muscular strength when fatigued are similar in both sexes. It appears there is currently no comparable data available on youth football players but if fatigue has a similar effect on dynamic knee stability there is an urgent need to improve the ability to resist fatigue through appropriate injury prevention programmes.

On the other hand, research by Kawakami et al. (1993) on the elbow flexors in 13 year old boys suggest eccentric and concentric torque production decrease at a similar rate when fatigued. This would imply that the FH/Q ratio may remain similar pre and post fatigue in children. This suggestion highlights the importance of future investigations on the knee joint after fatiguing exercise using female participants in order to gain an understanding of these mechanisms when fatigued in this at risk population.

2.15.3 Effect of fatigue on EMD

Similarly to the FH/Q ratio, data on the effect of muscle fatigue in adults on EMD is also sparse. Furthermore, there appear to be no studies investigating the effect of fatigue on EMD during childhood on either boys or girls. Howatson et al. (2010) examined the impact of damaging exercise in adult males on the EMD of the biceps brachii. They reported a significantly longer EMD 96 hour’s post exercise.

Similarly, Zhou et al. (1996) also reported that EMD was significantly longer after four periods of all out sprint cycling (40.4 Versus 63.4ms). Investigations on the neuromuscular fatigue in adult males following a football game are available. Rahnama et al. (2006) used EMG to investigate the effect of fatigue on the lower limb, reporting that EMG activity was significantly less after the exercise protocol.

When considering the generation of force and EMD of a muscle action, several components should be considered. These are; 1) conduction of action potentials along the T-tubule system; 2) release of calcium by the sarcoplasmic reticulum; 3) cross-bridge formation between actin and myosin filament and consequent tension development in the contractile component and 4) stretching of the series elastic component (Cavanagh and Komi, 1979). Fatigue may develop due to failure at one or more sites along this pathway for force production (Kent Braun, 1999, Allen et al., 2008). It is suggested that the main mechanisms for the lengthening of EMD with fatigue is from failure of muscle action potentials (Horita and Ishiko, 1987, Yavuz et al., 2010) or impaired excitation-contraction coupling (Kent Braun, 1999) and there is direct evidence to support these fatigue mechanisms in football (Mohr et al., 2005). Failure at any point of these two processes could result in the slowing down of the force of a contraction (Yavuz et al., 2010). Impairment of action potentials along the muscle membrane can be caused due to a potassium (K^+) efflux into the t-tubules during repeated muscle actions (Yavuz et al., 2010) which causes substantial membrane depolarization, failure of excitation and therefore a reduction in the force response (Allen et al., 2008). Action potentials therefore do not reach the depth of the muscles so calcium ion (Ca^{++}) release is reduced, slowing down the force of contraction (Yavuz et al., 2010). Moreover, impaired excitation-contraction coupling could occur at various points within the process; for example in the sarcoplasmic reticulum affecting the rate of Ca^{++} released (Allen et al., 2008). If there is a reduction of Ca^{++} released then the rate of force generation would be reduced and therefore prolong EMD when fatigued (Allen et al., 2008).

Studies on adult males show a significant increase in EMD following fatiguing protocols which could increase the relative risk of sustaining a knee injury. Further research is required throughout childhood in order to understand the mechanisms and help clarify the relative risk of non-contact ACL knee injuries in children when muscular fatigue is present.

2.15.4 Effect of fatigue on Leg Stiffness

There are a limited number of studies available that have investigated the effect of fatigue on leg stiffness in adults. Those studies that are available have used a variety of protocols to induce fatigue and the results are conflicting. Morin et al. (2011) reported an increase in leg stiffness following a 24 hour treadmill run whereas Dutto and Smith (2002) reported a decrease in leg stiffness following a treadmill run to exhaustion. In contrast, Girard et al. (2011) reported no significant change in leg stiffness following six 20m sprints, therefore making it difficult to determine the true effects of fatigue on leg stiffness. Hunter and Smith (2007) investigated various running characteristics such as oxygen uptake, optimum stride frequency and leg stiffness in experienced runners on a treadmill. They conclude that the effect of fatigue on leg stiffness is subject specific as some of their participants increased leg stiffness post fatigue, some decreased and some showed no significant change following one hour of maximal treadmill running.

There are currently no available studies that have explored the effects of football specific fatigue on leg stiffness in children. Given the incidence data indicating that non-contact ACL injuries are most likely to occur towards the end of a game when fatigue is present and that young girls are an at risk population for such injury, it is surprising there has been no investigations exploring the role of leg stiffness; a feed-forward mechanism of neuromuscular knee stability when fatigue is present.

2.15.5 Fatigue protocol

The fatigue effects of any activity can be assessed by testing the desired variable pre and post exercise, specific to football, a number of protocols have been developed in order to induce muscular fatigue to reflect actions and intensities performed in a competitive game. Football match play is intermittent with both high and low intensity activities throughout the game (Stolen et al., 2005). The physiological demands of football require players to complete a range of activities, thus the need to develop various components of fitness (Small, 2008) is vital for successful performance. During a 90 minute football match, elite male players cover around 10-12km from activities of various intensities (Stolen et al., 2005).

Although few studies have examined the physiological profile of female players, information is available and report females to cover a smaller distance than male players, however the intensity remain similar at around 70% of maximal oxygen intake (Rosenbloom et al., 2006).

Simulations have been developed to replicate both the physiological and mechanical demands of a competitive game and are often placed in one of two main categories, those that use a treadmill to recreate an activity profile or those that use a free-running protocol using repetitive intermittent shuttle runs (Small, 2008). A limitation of the treadmill based protocols is the inability to incorporate utility movements such as changing direction due to the nature of treadmill running; therefore free-running protocols are often favored. The Loughborough Intermittent Shuttle Test (LIST) developed by Nicholas and colleagues (2000) was designed to simulate the activity pattern characteristics of football. Although the test was reported to closely simulate both the physiological and metabolic responses associated with match play by the authors, questions were raised due to its inclusion of a run-to-exhaustion second part of the test (Small, 2008) which is not representative of match play, so therefore saw the development of the soccer-specific aerobic field test ($SAFT^{90}$).

The $SAFT^{90}$ is based on contemporary time-motion analysis using data obtained from English Championship level match play via Prozone and has been validated by (Lovell et al., 2008) to replicate the fatigue response of football match-play (Small et al., 2010). The free running protocol includes various changes in direction and speed over a 20m course with inclusion of utility movements such as walking, jogging, side stepping and sprinting and currently provides a protocol with the greatest ecological validity for a football specific field test (Small et al., 2010). A limitation of the protocol is that it only reflects the movement patterns and intensities of elite adult male football, however there is currently no youth or female football alternative.

There is currently no available data on how female youth football players may respond on a muscular and neuromuscular level to football specific fatigue which they encounter weekly over a sustained period of a competitive season. Fatigue has been implicated as a risk factor for injury and as female youth players face an increased relative risk of sustaining a non-contact ACL injury, there is an urgent need for research in this area.

2.16 Conclusion

Available literature has identified female athletes to be at a much greater relative risk of sustaining a non-contact ACL injury than their male counterparts. Furthermore, it is suggested that for the same amount of exposure, 13-18 year old girls are the most at risk group to sustain such injury. It is therefore surprising at the lack of empirical data on this age group.

Common ACL injury mechanisms have been identified as well as potential risk factors for female athletes. Muscular and neuromuscular mechanisms have been shown to be important aspects in reducing the relative risk of injury; however it is suggested that ACL injury in female athletes is a multifactorial problem which remains poorly understood and therefore requires further investigation. Evidence suggesting that females are more quadriceps dominant than males, coupled with reports that traditional football training may predispose an individual to quadriceps dominance and therefore ACL injury risk, highlights the need to explore FH/Q ratios and neuromuscular functioning in female players. This, as well as evidence indicating fatigue as a risk factor for injury makes exploring these mechanisms when football specific fatigue is present vital.

By developing complex study designs in order to examine a range of muscular and neuromuscular outcome variables in relation to fatigue, practitioners can begin to construct a more comprehensive and accurate understanding of the most relevant risk factors that negatively affect the stability of the knee joint. This will then hopefully allow potential risk factors to be identified and age and maturational based training strategies implemented to reduce the relative risk of injury.

This will be the first study to investigate the effect of football specific fatigue on the dynamic knee stability in elite female youth football players. In order to answer the research aims and objectives mentioned in the introduction of this thesis, this investigation will aim to answer the following research questions:

1. To what extent does football specific fatigue influence the functional hamstring to quadriceps ratio, electromechanical delay and leg stiffness in elite youth female football players?

2. To what extent do age and maturation related differences influence the functional hamstring to quadriceps ratio, electromechanical delay and leg stiffness in elite youth female football players?

3. To what extent are muscle specific compensatory mechanisms in place following football specific fatigue in elite youth female football players?

CHAPTER III

METHODS

3.1 Participants

Thirty-six females aged 12-18 years from an FA Women's Super League Team professional youth academy were recruited to participate in this study. Players were recruited from three age groups; those under 13 years of age (U13's [*n* = 14]), those under 15 years of age (U15's [*n* = 9]) and those under 17 years of age (U17's [*n* = 13]). Verbal consent was obtained from the club prior to approaching players, followed by parental consent and player assent (see appendix B and D). Participants were given an information sheet to explain the procedures involved as well as receiving verbal instructions (see appendix A).

All participants completed a health questionnaire (see appendix F) in accordance with the University of Gloucestershire sport and exercise laboratory procedures. Inclusion to the study was approved if the participants satisfied the acceptance criterion as described in the health questionnaire flow chart. There were 2 exclusion criteria in this study: (1) histories of orthopedic problems, such as episodes of hamstrings injuries, fractures, surgery or pain in the spine or hamstring muscles over the past six months; (2) self reported presence of delayed onset muscle soreness (DOMS) at a testing session. Participants were instructed to avoid their regular training regimens throughout the experimental period and not to take part in any vigorous physical activity 48 hours proceeding each testing day. None of the participants reported any form of musculoskeletal disorder at the time of testing.

3.1.1 Ethical Considerations

Ethical approval had been obtained from the University of Gloucestershire's Research Ethics Committee (RESC, [see appendix E]). RESC approved laboratory procedures and university guidelines for working with children were followed at all times and all researchers involved in the study had obtained a Criminal Record Bureau (CRB) check before data collection began.

Participants were also made aware that they could withdraw at any point of the study without affecting their relationship with the university, research team or the club. All the data collected was stored on a computer using an ID code for each individual participant and only accessible by the research team or club if prior consent was given. Any hard copies of data were stored in a lockable draw and only available to the principal investigator.

3.2 Study Design

The researchers initially travelled to a club training session in order to collect leg stiffness data from a hopping task using a portable contact mat. Participants were then required to visit the laboratory at the university on two separate occasions; once for a habituation session and then once for the pre/post fatigue testing. *(Figure 3.1)*.

The purpose of the habituation session was to familiarise the participants with the testing protocol on the isokinetic dynamometer as well as introduce them to the SAFT^{90}. Isokinetic habituation or familiarisation sessions have been indicated as important in order to reduce the effect of learning on the test data as well as introduce the participants to eccentric cycles to decrease the risk of injury (De Ste Croix et al., 2003). This session was also used to collect anthropometric data in order to predict maturational status defined as years from peak height velocity (Mirwald et al., 2002). Participants also repeated the hopping task in a pre-fatigued state in order to determine the inter-session reliability of the method.

When the participants visited the university for the actual testing session they performed baseline EMD tests and performed the isokinetic/EMG cycles in a pre-fatigued state. They then performed a football-specific fatiguing task; repeating the leg stiffness task immediately upon finishing, and finally repeated the isokinetic/EMG tests after in a post-fatigued state.

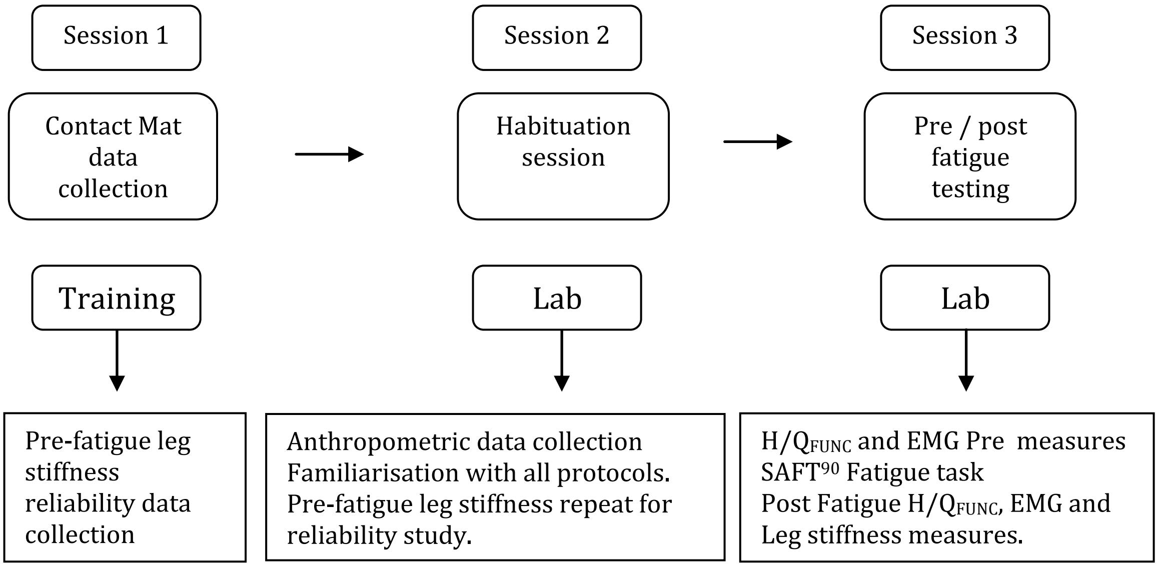


Figure 3.1: Research design schematic

3.3 Procedures

3.3.1 Anthropometry

Age was computed from date of birth and date of testing. Stature and body mass were measured on the first visit to the laboratory according to the procedures of Weiner and Lourie (1981) - using a Stadiometer (Holtain Harpenden, Crymych, UK) and calibrated balance beam scales (Weylux Birmingham, UK). Sitting height was measured with a sitting height table (Holtain Harpenden, Crymych, UK) with the posterior surface of the knee tight against the measuring box. Age from PHV was predicted using *Equation 3.1* of Mirwald et al. (2002) which indicated that maturity offset can be estimated within an error of ± 1 year 95% of the time.

Equation 3.1 Mirwald et al. (2002) equation.

For females: Maturity offset = − 9.376 + (0.0001882 x (leg length x sitting height)) + (− 0.0022 x (age x leg length)) + (0.005841 x (age x sitting height)) + (0.002658 age x weight) + (0.07693 x (mass by stature ratio)).

3.3.2 Leg stiffness

Sub-maximal two-legged hopping was performed at a frequency of 2.5 Hz. Participants were asked to hop two-legged on top of the contact mat for a period of 20 consecutive hops at the given frequency. Participants were instructed to: keep hands on the hips at all times to avoid upper body interference (Lees et al., 2004); jump and land on the same spot; land with legs fully extended and to look forward at a fixed position to aid balance maintenance (Lloyd et al., 2009). Adherence to these instructions was carefully monitored by the tester every time the participants completed the test.

Hopping frequency was maintained by an audio signal from a quartz metronome (SQ-44, Seiko, UK). Monitoring of hopping frequency using the digital metronome, as opposed to allowing participants to self select their preferred frequency, enabled greater control of movement coordination in the lower extremities whilst hopping. The choice of 2.5 Hz is within the boundaries previously highlighted as allowing the broadest possible range of hopping frequencies (1.5 Hz – 3.0 Hz) by Hobara et al. (2009). Frequencies below 1.5 Hz have led to an inability of maintaining true spring-mass model behaviour in the lower extremities (Farley et al., 1991), whilst frequencies above 3.0 Hz have prevented the successful maintenance of desired hopping pace (Hobara et al., 2008). Because those studies used adult populations, the choice of 2.5Hz was deemed more attainable and sustainable for younger participants. All jumps were performed on a mobile contact mat (Smartjump, Fusion Sport, Australia), and data instantaneously collected via a hand-held PDA (iPAQ, Hewlett Packard, USA). Leg stiffness was calculated from the sub-maximal hopping test using *Equation 3.2:*

Equation 3.2 Leg stiffness equation

$$K_N = \frac{M.\pi(T_f + T_c)}{T_c^2\left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4}\right)} \qquad \text{(in N x m}^{-1}\text{)}$$

Where K_n is the leg stiffness, as calculated using a contact mat, M is total body mass, T_c the ground contact time and T_f the flight time (Dalleau et al., 2004). This method and frequency has been previously shown to be reliable and valid in paediatric populations when compared to the criterion force plate methods (Lloyd et al., 2009). The leg stiffness data was then normalised relative to body mass and limb length (stiffness x [leg length / body mass]) to give relative leg stiffness due to the close association between body mass and leg stiffness and the mechanical influence of limb length on the movement according to the work of McMahon and Cheng (1990).

3.3.3 Leg Stiffness Reliability

The leg stiffness testing procedure was completed on two separate occasions, in order to test the inter-session reliability of the method. Participants completed four repetitions of the sub-maximal hopping task on each visit with a one minute rest in between repetitions in order to test the trial-to-trial intra-session reliability of the method.

For all leg stiffness tests completed in this study, ten consecutive acceptable hops were used for analysis and normalised relative to body mass and limb length for each participant. The selection criteria of these hops were based on ten consecutive hops where the participant was closest to the selected frequency of 2.5Hz (Dalleau et al., 2004, Lloyd et al., 2009). This was done for each of the four repetitions taking the average of the best two repetition data sets and using this value for statistical analysis.

3.3.4 FH/Q ratio

Torque assessments were made on the dominant leg, determined by kicking preference. A recent study by Delextrat et al. (2011) on the effect of a simulated soccer match on the FH/Q ratio in amateur female players found no significant difference between the dominant and non-dominant legs (determined by kicking preference), therefore the dominant limb was chosen in the current study. The tested range of motion was from 90° to 0° of knee flexion (0° = full extension), determined for each participant individually by placing mechanical stops at the beginning and end of their full active range of motion *(Figure 3.2)*. The range stop control was set as soft (setting 2) so as to reduce the possibility of sudden resistance at the end of each range of motion.

Each session began with a standardised warm-up consisting of two minutes cycling on a Monark cycle ergometer 814E (Monark, Varberg Sweden) at a moderate intensity and two minutes of stretching of the hamstrings and quadriceps muscles (De Ste Croix et al., 2007). Participants were positioned in prone with the axis of rotation of the dominant knee (lateral epicondyle) aligned carefully with the axis of rotation of the dynamometer. The lever arm length was then adjusted for each participant so that it rested on the tibia approximately 3cm above the medial malleolus (De Ste Croix et al., 2007). Gravity corrections for limb mass were performed before each isokinetic assessment in accordance with the manufacturer's instructions (Biodex Pro Manual, Applications/ Operations, Biodex Medical Systems, Inc., Shirley, NY). Therefore, at the start of each test session the participant was asked to relax their leg so that passive determination of the effects of gravity on the limb and lever arm could be accounted for; the tested leg was held by the examiner at the full extension position.

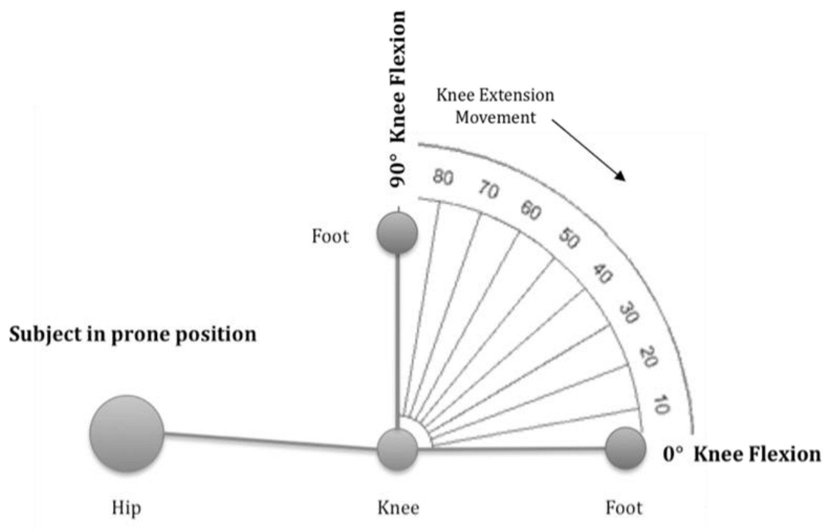


Figure 3.2 Diagram illustrating knee joint angles as referenced in this study.

All assessments were performed in a prone position for both concentric and eccentric testing *(Plate 3.1)*. Testing took place at three angular velocities (60˚/s, 120˚/s and 180˚/s) for both concentric and eccentric actions. Previous literature has used 60˚/s and 180˚/s in paediatric populations (Kellis et al., 2001, Gerodimos et al., 2003) and a third angular velocity in between these values was selected in order to receive data at a range of velocities in this population.

The concentric cycle was undertaken first, as it is suggested that eccentric muscle actions may potentiate the following concentric action if performed first (De Ste Croix et al., 2003). Testing started with the knee at 90° with extension always being the first action and began with the slowest angular velocity (60˚/s) and continued with increasing angular velocity (120˚/s followed by 180˚/s) to reduce the risk of injury (Gaul, 1996). Concentric quadriceps muscle strength was measured during dual concentric-concentric actions and the passive eccentric mode was used to determine eccentric torque during eccentric/eccentric cycles. In the concentric quadriceps measurement participants were instructed to push the lever arm up, and pull it down as hard and fast as possible. This was repeated three times at each angular velocity (3 repetitions x 3 sets) with a 30 second rest period between movements at different angular velocity. However, in the eccentric hamstring measurement participants were instructed to resist the lever arm as hard and as fast as possible. Three single maximal efforts were performed at each angular velocity with a ten second rest in between each repetition of the same velocity and a 30 second rest between movements of a different velocity (1 repetition x 9 sets). This was done to allow the EMD to be calculated on all nine repetitions.

Plate 3.1 Prone position during isokinetic testing

In the concentric-concentric cycle, participants were counted down to begin the movement by one of the principal investigators. The words “Three, two, one, GO” were said with the participant beginning to push on the word go. In the eccentric-eccentric cycle, there was no count down as EMD was being calculated and therefore relied on the participant's reaction to a stimulus. Participants were asked if they were ready and to relax and then wait for the external triggers discussed in the next section (3.3.5 Electromyography) before beginning to resist the lever arm.

Participants were instructed to push, pull or resist the lever arm as hard and as fast as possible throughout the entire range of motion. Standardised verbal encouragement was given before each maximal effort and visual feedback of the recorded torque provided as it is suggested children perform better when feedback is given to motivate them (De Ste Croix et al., 2003).

PT values were recorded during concentric quadriceps and eccentric hamstrings action and later used to calculate the functional hamstring to quadriceps ratio by expressing average eccentric hamstrings torque to average concentric quadriceps (as a ratio) at three angular velocities (60˚/s, 120˚/s and 180˚/s) and at three knee angles (10°, 20° and 30°) for functional relevance.

3.3.5 Electromyography

The electromyography was quantified with an 8-channel DelSys EMG telemetry system (DelSys Myomonitor III, DelSys Inc., Boston, MA, USA) to investigate the activity of the biceps femoris, semitendinosus and gastrocnemious during the eccentric movement to determine EMD. For maximum signal detection each 3 x 2cm bipolar surface electrode (DE- 2.3 MA; DelSys Inc., Boston, MA, USA) were positioned in the mid-line of the belly of the muscle; with an inter-electrode distance of 2cm, perpendicular to the muscle fibres because in this location the electromyographic signal with the greatest amplitude is detected (Gleeson, 2001). When in a prone position participants were asked to resist a force applied by the researcher and flex the knee in order to palpate the hamstring muscles and accurately attach the electrode. Following this participants were asked to point their toes in order to palpate the medial gastrocnemious muscle and attach the electrode.

The biodex square wave synchronisation pulse is configurable via the biodex ASA software allowing the triggering of the EMG software. The EMG system signal was interfaced to the Biodex via a trigger box. The EMG works software offers full triggering capabilities to control the start and stop of all data acquisition systems in a given experimental setup. The biodex ASA software is used to activate the biodex square wave signal output to trigger the start signal. The Trigger Module only accepts signals that are between 0 to 5 volts, and could be configured for either positive-edge signals or negative-edge signals. Positive-edge or "rising" was defined to start from 0V and rise to 5V. The transition points of these voltages were defined as the event. Once the 5V level is reached, the duration of the trigger pulse is kept in the high state for a minimum amount of time before returning back to the low state. The trigger box detects a change in the biodex output square wave signal, so that when the appropriate voltage change had taken place, the trigger box triggered the EMG PC (laptop) software to start recording the EMG data. When the hold button (Biodex) is pressed by the researcher the biodex signal (trigger) is switched on. Therefore, the EMG and biodex are completely time aligned.

Three electrodes were placed on the dominant limb determined again by kicking preference *(Plate 3.2)* on the medial and lateral hamstring muscles represented by the semitendinosus (ST) and biceps femoris (BF), as well as the gastrocnemious (G) with the reference electrode placed on the lateral malleolus as recommended by the Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) project standards (Hermens et al., 2000). The standard for the skin preparation is an electrical resistance between the three electrodes of less than 5kΩ for a very good skin impedance condition (Konrad, 2005). The skin was cleaned with an alcohol wipe to improve application of the electrodes and reduce the acceptable impedance to below 5kΩ (Konrad, 2005). Participants were also asked not to use any type of moisturiser on their legs during testing to allow adhesion of electrodes.

Following the application of surface electrodes a baseline measure of EMG activity was recorded with the participant in a prone position with the leg fully extended and supported by the massage table. Participants were instructed to relax and lay as still as possible whilst three measurements each lasting 10 seconds were taken. If muscle activity was evident through visual inspection of the participant and/or the recording this procedure was repeated or the electrodes were repositioned until the investigators were confident that a true baseline value was recorded (Konrad, 2005). The target baseline value used was 1-2 μV with the average baseline noise not exceeding 5 μV (Konrad, 2005). A permanent pen was then used to mark the position of electrodes for repeat testing *(Plate 3.3).*

Plate 3.2 An illustration of the positioning of the electrodes

Plate 3.3 Marking of electrodes.

Participants were instructed to perform eccentric PT assessments of the hamstring muscles in the prone position on the dominant leg (using the same isokinetic procedures highlighted previously). Participants were provided with two external triggers for the start of the movement of the lever arm: 1) the physical movement of the lever arm; 2) a light appeared on the trigger box when the movement was initiated and at a constant velocity *(Figure 3.3).* Participants were encouraged to relax the leg as much as possible before the movement to reduce the influence of pre-activation on the measurement. If the investigators could observe that pre-activation was taking place; identified by tensing of the lower limb muscles, they would remind the participant to relax before starting the lever arm. The participants were reminded to exert maximal voluntary actions as quickly as possible when seeing the light and feeling the lever arm move.

Figure 3.3 Trigger port indicating the trigger light

Raw EMG data was collected at a sampling frequency of 1024 Hz and sent directly to the DelSys Acquisition software package set up on a Toshiba Laptop (L20, Toshiba Corp. Tokyo, Japan). The EMG unit includes a common mode rejection ratio of >80 dB and an amplifier gain of 1000. Raw EMG data was band pass filtered at 20 – 450 Hz using the DelSys Acquisition software.

The EMD was determined by the time interval between the onset of EMG and force development according to the procedure developed by Zhou et al. (1995). Based on this procedure the onset of EMD was determined as a change from the EMG mean baseline level to +15 μV deviation and the offset of EMD was determined as the time taken (ms) to generate 9.6-Nm torque *(Figure 3.4).* The maximal EMD value was determined as the shortest EMD from the three measurements for each angular velocity.

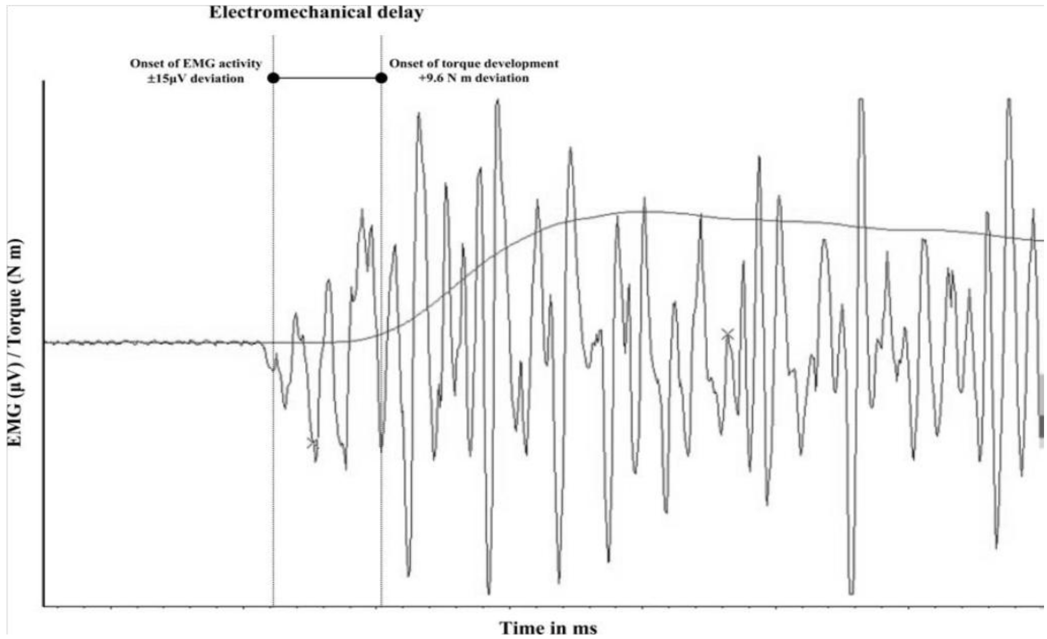


Figure 3.4 An illustration of the process used to determine the EMD (Zhou et al., 1995)

3.3.6 SAFT^{90} Protocol

The SAFT^{90} is based on contemporary time-motion analysis using data obtained from English Championship level match play via Prozone and has been validated by Lovell et al. (2008) to replicate the fatigue response of football match-play (Small et al., 2010). The design of the course is based around a shuttle run over a 20m distance, with the incorporation of four positioned poles for the participants to navigate using movements such as walking, jogging, side stepping and sprinting *(Figure 3.5)*.

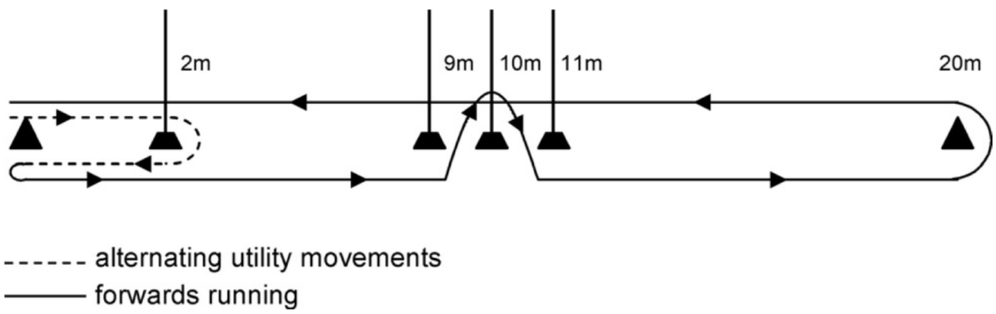


Figure 3.5 A diagrammatic representation of the SAFT^{90} course

The course was performed with the participant performing either backwards running or sidestepping around the first field pole, followed by forward running through the course, navigating the middle three field poles. No contact actions such as kicking or tackling were performed. The movement intensity and activity performed by the participants whilst completing the SAFT^{90} course were maintained using verbal signals on an audio CD. The audio CD contains a 15 min activity protocol which was repeated randomly and intermittently in order to last for the duration of a game the participant usually competes in, including a passive rest interval equivalent to those experienced on a match day *(Table 3.1)*. The coach and a member of the research team provided strong verbal encouragement throughout the protocol to help maintain participant effort. Participants completed the course in groups of three or four staggered at 30 minute intervals *(Plate 3.4)*.

Table 3.1 Academy game duration.

Age Group	Format	Passive rest duration	Total playing time
Under 13's	3 x 25 minutes	2 minutes	75 minutes
Unger 15's	2 x 40 minutes	10 minutes	80 minutes
Under 17's	2 x 45 minutes	15 minutes	90 minutes

Before any testing was completed, players performed a standard 10 minute warm up which was usually performed at their club before matches. This included a period of sub-maximal running and familiar dynamic mobiliastion exercises. All procedures can be viewed on the CD attached to this thesis.

Plate 3.4 U13 participants performing the SAFT^{90}

3.4 Statistical Analysis

Intra-session reliability of relative leg stiffness data was analysed using Microsoft Office Excel 2007. Means and standard deviations were calculated for each trial of the jump protocol. Average intraclass correlation coefficients (ICC) were determined to assess the trial-to-trial reliability of the hopping test data. Mean coefficients of variation (CV) were calculated using the anti-logged root mean square error, obtained from the two-way ANOVAs on log-transformed data (Hopkins, 2000b), with log-transformation reducing the effects of any non-uniformity of error (Hopkins, 2000a). Ninety-five percent confidence intervals (95% CI) were reported for the coefficient of variation. This method of analysis was used and favoured over limits of agreement as it was an exact replication of the method and analysis used in a recent study assessing the reliability and validity of this field based measure for leg stiffness (Lloyd et al., 2009). Furthermore, CV provides an associated error in a form that is useful when looking at changes over time through repeated measures, which the current study does. A two-tailed paired t-test using the Statistical package for Social Sciences (SPSS, v. 19.0 for Windows; SPSS Inc, Chicago) was performed to determine the existence of a statistically significant difference between the relative leg stiffness data recorded on the two testing days in order to explore the inter-session reliability of the method. Mean differences and standard deviations were reported for the sub-maximal hopping task on both occasions.

SPSS was used to perform all other statistical analyses. Firstly the distribution of raw data sets was checked for homogeneity and skewness and the assumption of normality was verified using the Kolmogorov-Smirnov test. Descriptive statistics including means and standard deviations were calculated for each measure. A 3 x 2 x 3 x 3 (group; time; angle and velocity) Mixed Model analysis of variance (ANOVA) for the H/Q_{FUNC}, and a 3 x 2 (group and time) Mixed Model ANOVA for leg stiffness was used to explore interaction and main effects. A 3 x 3 x 3 x 2 (muscle; group; velocity and time) Mixed Model ANOVA was used to explore interaction and main effects for EMD. Significant interaction or main effects were further examined using Bonferroni-corrected post hoc tests. Main effects were calculated irrespective of time, angle and velocity. The level of significance for all statistical testing was set at $P \leq 0.05$. Percent change scores were also reported.

CHAPTER IV

RESULTS

4.1 Participant Characteristics

A total of 36 participants completed the study with 14 players in the U13's, 9 in the U15's and 13 in the U17's. Age was determined from date of birth and the test date. Based on kicking preference, four participants determined their left leg as their dominant leg, with the remaining 32 participants identifying their right leg. Playing position was self reported identifying 3 goal keepers, 11 defenders, 18 midfielders and 4 strikers. Only one participant in the U13 age group self reported that they had started menstruating and was in the follicular phase during testing. Five participants in the U15 and 11 participants in the U17 age group self reported that they were menstruating (two U17 participants were taking the contraceptive pill) and were in the following phases during testing; Luteal phase (n=10), follicular phase (n=7). Participant characteristics can be seen in *Table 4.1*. There were significant group differences in stature, body mass, leg length and offset from PHV. Total distance covered during the SAFT^{90} was 6320 ± 69m (U13), 10525 ± 592m (U15) and 10590 ± 662m (U17) for each age group respectively.

Table 4.1 Participant characteristics by age group

	Under 13	Under 15	Under 17
Age (y)	12.1 ± 0.5	13.9 ± 0.6	15.8 ± 0.5
Stature (m)	1.46 ± 0.06*	1.59 ± 0.08	1.66 ± 0.06
Body mass (kg)	40.8 ± 6.7*	51.9 ± 8.8	61.9 ± 8.2
Leg length (cm)	68.6 ± 3.4*	73.4 ± 3.8	79.8 ± 3.8
Offset from PHV (y)	-0.28 ± 0.55*	1.11 ± 0.55	2.93 ± 0.58

* Significant difference between groups

4.2 FH/Q ratio

Mean (SD) data for FH/Q ratio by angle, angular velocity and age group, pre and post the football specific fatigue task can be seen in *Table 4.2.* A significant interaction effect for time x angle ($F_{2,34}$ = 3.914, p = 0.030) was found for the FH/Q

Table 4.2 FH/Q ratio pre and post fatigue by age group, movement velocity and joint angle

Velocity/Angle	FH/Q ratio Pre Fatigue			FH/Q ratio Post Fatigue		
0-10°	U13	U15	U17	U13	U15	U17
60°/s	1.40 ± 1.13	1.79 ± 1.01	1.42 ± 0.70	1.59 ± 1.61	0.95 ± 1.18	1.31 ± 0.68†
120°/s	2.01 ± 1.09	1.43 ± 0.92	1.49 ± 0.79	1.71 ± 1.38	1.27 ± 1.32	1.04 ± 1.02
180°/s	1.62 ± 1.15	0.75 ± 0.75	1.08 ± 0.57	1.45 ± 0.92	0.89 ± 0.49	1.10 ± 1.10
10-20°						
60°/s	1.50 ± 0.63	1.75 ± 0.86	1.30 ± 0.57	1.69 ± 1.45	1.34 ± 1.24	2.17 ± 1.08†
120°/s	1.63 ± 0.59	1.93 ± 0.88	1.90 ± 0.75	1.71 ± 1.35	1.43 ± 0.62	1.58 ± 1.04
180°/s	1.76 ± 0.65	2.09 ± 1.23	1.70 ± 0.57	1.76 ± 0.88	1.60 ± 0.42	1.99 ± 1.39
20-30°						
60°/s	1.27 ± 0.40	1.35 ± 0.54	1.18 ± 0.26	1.78 ± 1.40	1.03 ± 0.50	2.30 ± 1.04†
120°/s	1.38 ± 0.45	1.46 ± 0.48	1.46 ± 0.34	1.36 ± 1.05	1.23 ± 0.37	1.88 ± 0.93
180°/s	1.54 ± 0.40	1.52 ± 0.69	1.49 ± 0.30	1.50 ± 0.93	1.33 ± 0.30	2.07 ± 1.13

† Significant time x angle interaction effect

ratio. Post hoc analysis revealed that this difference was between 0-10° and 10-20° pre (p = 0.004) and post (p = 0.003) fatigue (*Figure 4.1*). This interaction demonstrates that the ratio decreased from pre to post fatigue at 0-10° (1.56 ± 0.94 versus 1.34 ± 1.07 [14.1% decrease]), remained similar at 10-20° (1.81 ± 0.74 versus 1.83 ± 1.12 [1.1% increase]) and increased at 20-30° (1.48 ± 0.42 versus 1.68 ± 1.02 [13.5% increase]). The difference in the absolute change in the FH/Q ratio from pre to post fatigue between 0-10° and 20-30° was 0.44. No other significant interaction effects were observed.

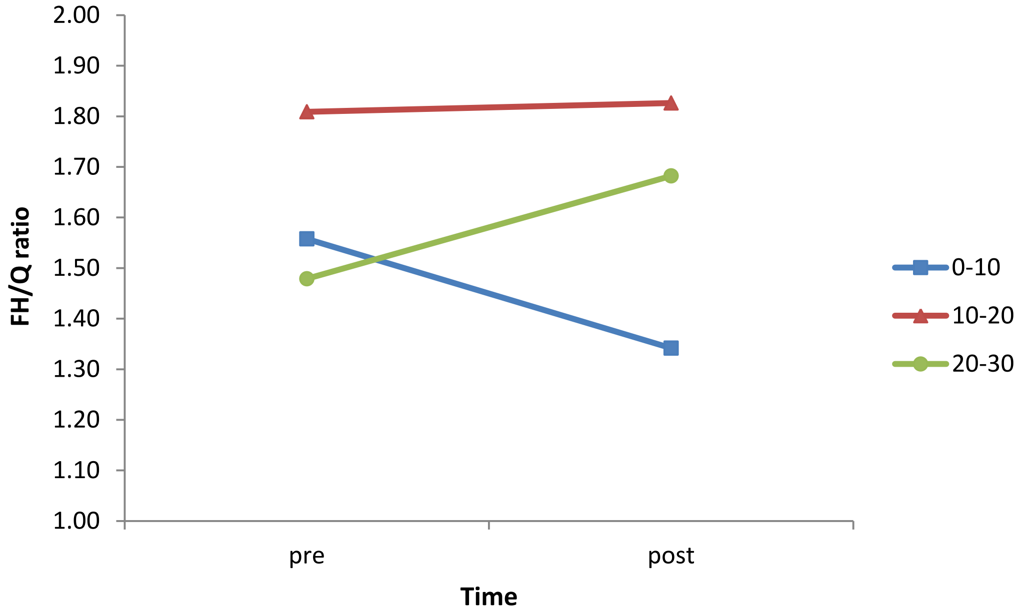


Figure 4.1 FH/Q ratio pre and post fatigue by joint angle

A significant main effect for angle ($F_{2,34}$ = 12.178, p = 0.002) was found with the ratio significantly higher between 10-20° than 0-10° (p = 0.002) and 20-30° (p = 0.003) *(Figure 4.1).* This main effect demonstrates that the ratio is higher at 10-20° than 0-10° (1.82 ± 0.81 versus 1.45± 1.31 [25.5% increase]) and higher at 10-20° than 20-30° (1.82 ± 0.81 versus 1.58 ± 0.60 [13.2% increase]). Importantly, there were no main effects for time (pre fatigue 1.58 ± 0.67 versus post fatigue 1.68 ± 0.9 [6.3% increase]).

Although the time x group interaction effect did not reach statistical significance ($F_{2,34}$ = 2.299, p = 0.07) there were age related differences in the response to the football specific fatigue task. The FH/Q ratio remained similar in the U13s (1.71 ± 0.71 versus 1.81 ± 1.15 [5.8% increase]), decreased in the U15s (1.58 ± 0.78 versus 1.33 ± 0.70 [15.8% decrease) and increased in the U17s (1.53 ± 0.53 versus 1.79 ± 1.00 [17% increase]) *(Figure 4.2)*.

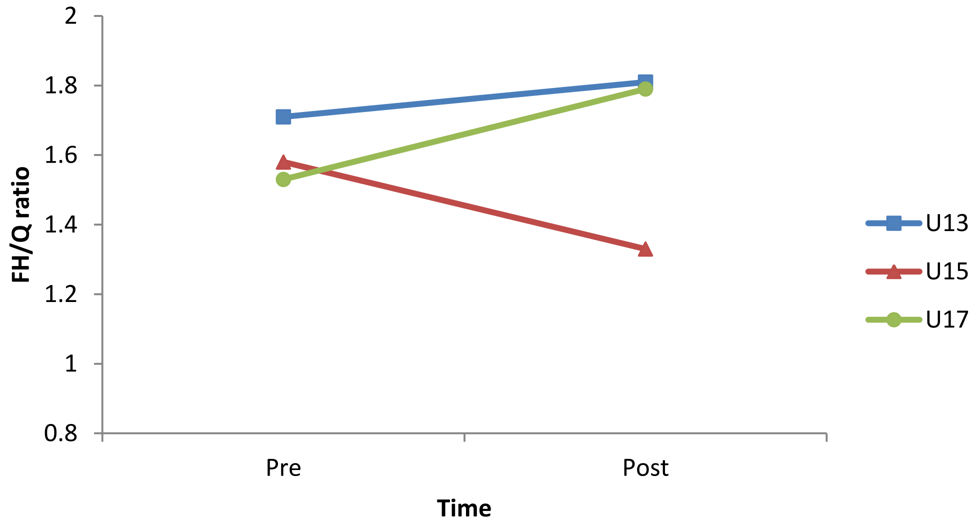


Figure 4.2 FH/Q ratio by time and group

4.3 Leg Stiffness

4.3.1Leg stiffness reliability

A high average intraclass correlation coefficient (r = 0.9; 0.80-0.95) was reported for all measures as well as a moderate coefficient of variance (9.5%; 7.8-12.2) when assessing the trial to trial reliability of the jump protocol. No statistical significant difference existed between the relative leg stiffness data recorded on the two testing days (p = 0.152).

4.3.2 Relative leg stiffness

Mean (SD) data for relative leg stiffness by age group, pre and post fatigue can be found in *Table 4.3.* Mixed Model ANOVA revealed a significant time x group interaction effect ($F_{2,34}$ = 4.295, p = 0.022) for relative leg stiffness but no significant main effects of group or time. Post hoc analysis revealed that this difference was between the U13 and U17 (p = 0.008) and U15 and U17 (p = 0.005) age groups pre fatigue *(Figure 4.3)*. The U13 age group showed a slight decrease in leg stiffness (4.9% decrease) compared to an increase in leg stiffness in the U17 age group post fatigue (12.3% increase). There was an individualised response to fatigue in the U15 age group with 4 participants increasing and five participants decreasing in leg stiffness (1.5% increase). Most participants' stiffness decreased in the U13 age group (n=10) but a few did increase their stiffness (n=4). All girls in the U17 age group increased stiffness post fatigue.

Table 4.3 Relative leg stiffness (dimensionless) by group and time

Group	Pre Fatigue	Post Fatigue
U13	44.6 ± 5.5*	42.4 ± 7.7
U15	46.4 ± 8.8*	47.1 ± 6.2
U17	36.5 ± 6.6*	41.0 ± 6.1

* Significant group by time interaction effect

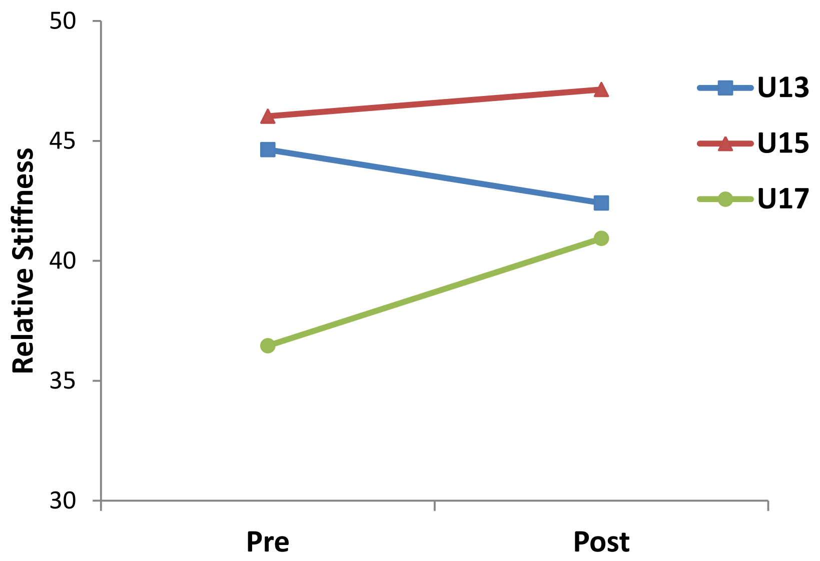


Figure 4.3 Relative leg stiffness pre and post fatigue by group

4.4 EMD

Mean (SD) data for EMD by age group, pre and post fatigue can be found in *Table 4.4.* Data is presented for each muscle group and split by movement velocity. Mixed Model ANOVA revealed a significant time x group interaction effect ($F_{2,34}$ = 3.404, *p*

= 0.046). No other interaction effects were observed. Post hoc analysis revealed that EMD was significantly longer in the U13 age group compared with the U15 (p = 0.011) and U17 (p = 0.021) groups and this difference was greater post fatigue (percentage increase in EMD from pre to post fatigue was 65.5% [U13], 43% [U15] and 60.9% [U17] respectively). These data can be seen in *Figures 4.4, 4.5* and *4.6.*

A significant main effect for time ($F_{1,35}$ =10.031, p = 0.000) and group ($F_{2,34}$ =6.356, p = 0.005) were also observed. Post hoc analysis revealed irrespective of group, muscle or movement velocity EMD was significantly longer post fatigue compared with pre fatigue (p = 0.000 [58.4% increase]) which can be seen in *Table 4.4*. Likewise, irrespective of time, muscle or movement velocity EMD was significantly longer in the U13 age group compared with the U15 (p = 0.011, 158 ± 66ms versus 113 ± 39ms [15.8% longer]) and U17 (p = 0.021, 158 ± 6ms versus 120 ± 40ms [24.1% longer]) age groups. There were no significant differences in EMD between the U15 and U17 age groups (113 ± 39ms versus 120 ± 40ms [6.2% longer) (see *Table 4.4* and *Figure 4.4, 4.5* and *4.6*). No significant (p > 0.05) main effects for muscle (132±51ms [BF], 133±52ms [ST], 127±63ms [G]) or movement velocity (139±69ms [60°/**s**], 122±46ms [120°/**s**], 131±51ms [180°/s]) were found.

Table 4.4 EMD pre and post fatigue by age group, muscle and movement velocity

Muscle/velocity	EMD Pre fatigue (ms)				EMD Post fatigue (ms)				% Change
Biceps femoris	**U13**	**U15**	**U17**	**Combined**	**U13**	**U15**	**U17**	**Combined**	
60	136 ± 62*	99 ± 36	96 ± 35	**113 ± 51**	220 ±111*	143 ± 44	157 ± 52	**179 ± 85**	**58%**
120	103 ± 32*	86 ± 28	95 ± 36	**96 ± 32**	178 ± 57*	127 ± 42	146 ± 40	**154 ± 51**	**60%**
180	117 ± 38*	93 ± 27	85 ± 33	**100 ± 136**	197 ± 60*	145 ± 46	148 ± 32	**167 ± 53**	**67%**
Semitendinosus									
60	144 ± 54	97 ± 34	97 ± 40	**116 ± 49**	223 ± 106	141 ± 46	153 ± 48	**153 ± 48**	**53%**
120	106 ± 31	96 ± 37	95 ± 35	**100 ± 33**	179 ± 45	125 ± 42	141 ± 36	**152 ± 46**	**52%**
180	124 ± 46	101 ± 41	84 ± 28	**104 ± 42**	200 ± 62	150 ± 56	141 ± 39	**167 ± 59**	**61%**
Gastrocnemious									
60	124 ± 61	79 ± 17	102 ± 61	**105 ± 55**	212 ± 122	11 7 ± 42	165 ± 45	**171 ± 91**	**63%**
120	97 ± 48	93 ± 24	92 ± 35	**94 ± 38**	185 ± 102	111 ± 42	137 ± 46	**150 ± 78**	**60%**
180	123 ± 68	92 ± 43	81 ± 31	**101 ± 53**	177 ± 80	145 ± 53	144 ± 42	**157 ± 63**	**55%**
All combined	**119 ± 49‡**	**93 ± 32**	**92 ± 37**	**101 ± 43†**	**197 ± 83‡**	**133 ± 46**	**148 ± 42**	**160 ± 67†**	**58%**

* Significant group x time interaction effect
† Significant main effect for time
‡ Significant main effect for group

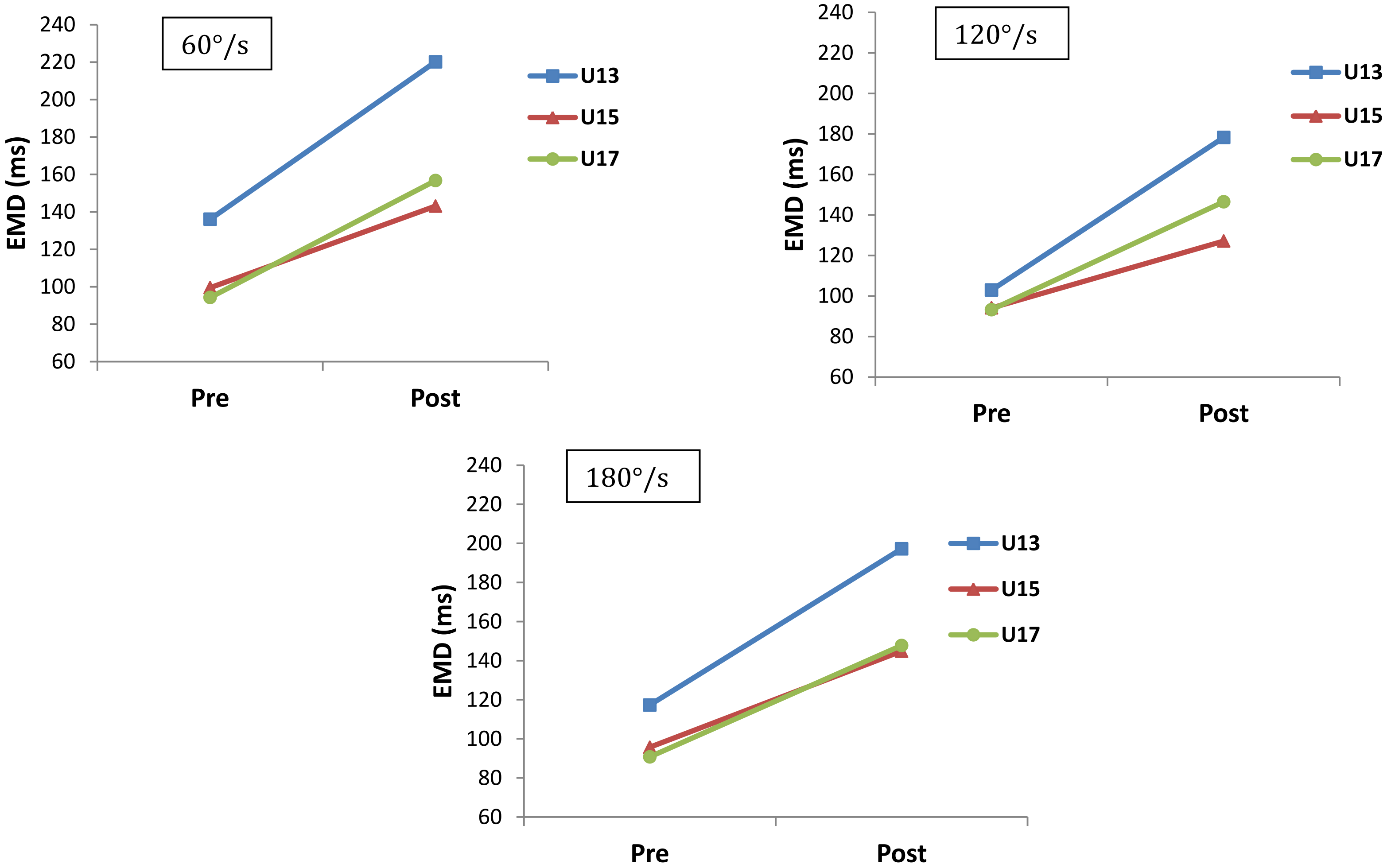


Figure 4.4 EMD by group pre and post fatigue for the biceps femoris (BF)

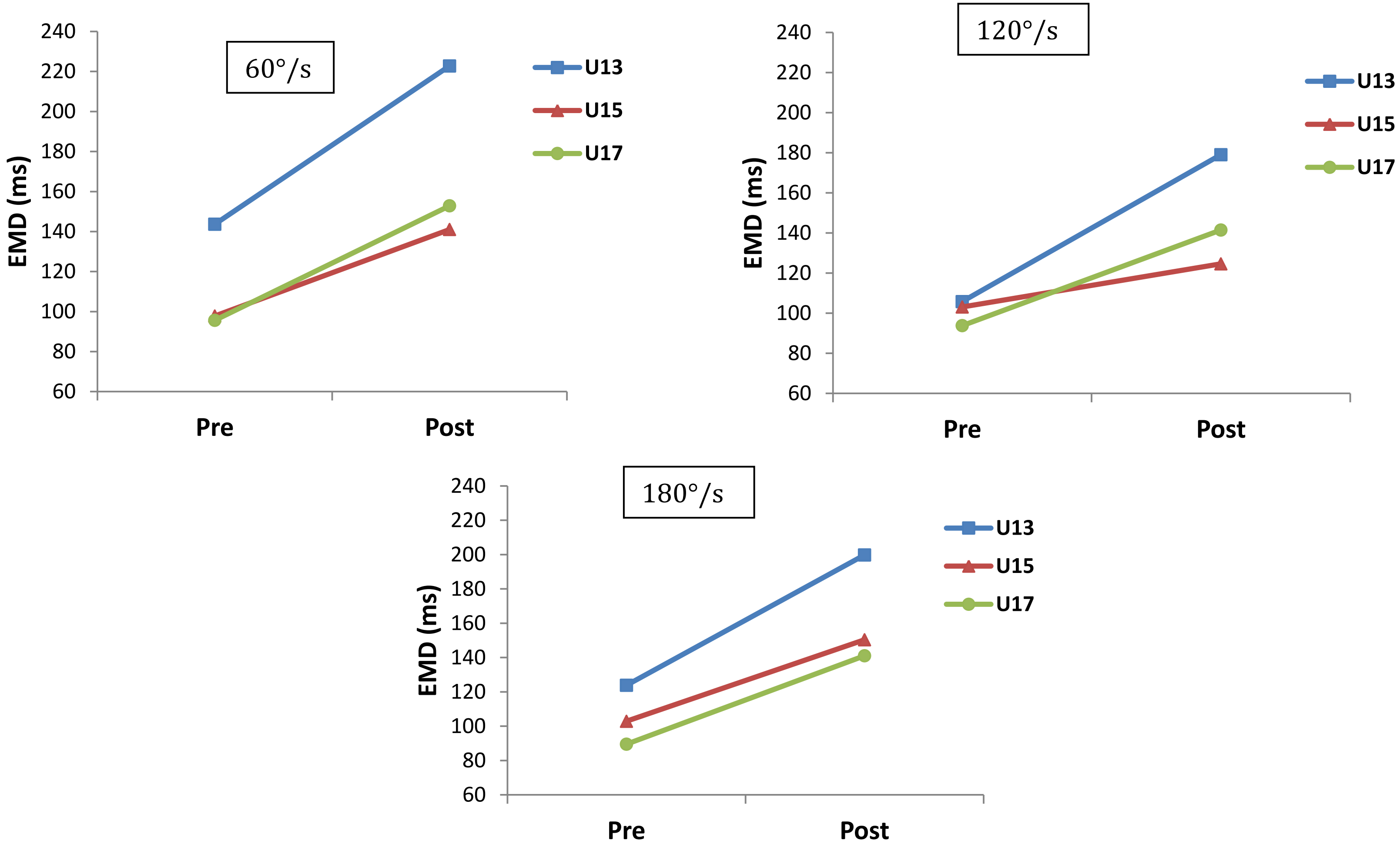


Figure 4.5 EMD by group pre and post fatigue for the semitendinosus (ST)

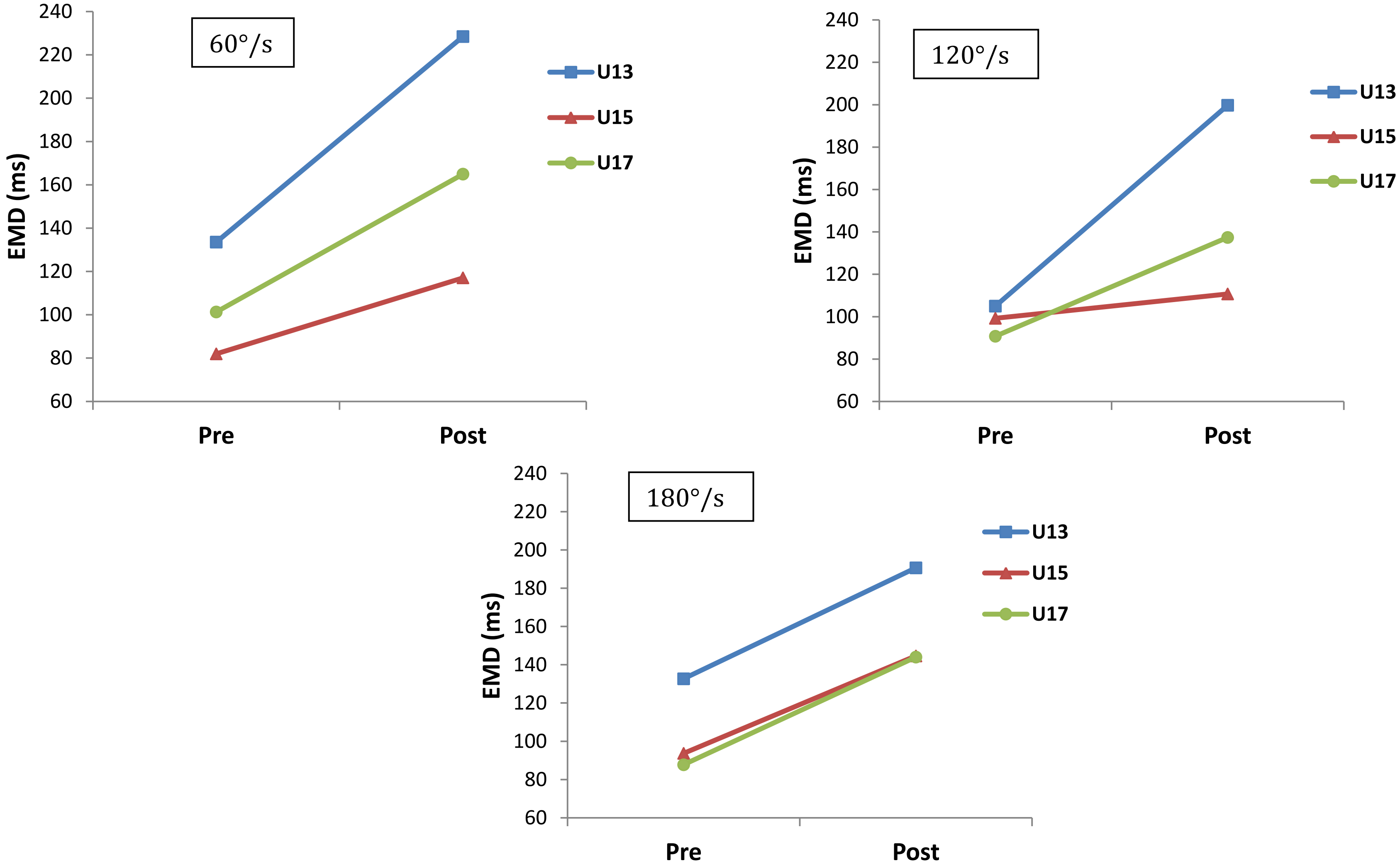


Figure 4.6 EMD by group pre and post fatigue for the gastrocnemious (G)

4.5 Summary of Results

- A time by angle interaction effect demonstrated a significant decrease in the FH/Q ratio post fatigue, irrespective of age between 0-10° of knee flexion, compared with an increase at more flexed angles.

- Age related differences between groups FH/Q ratio response to the fatigue task were present although they did not reach statistical significance. The ratio remained similar in the U13's, decreased in the U15's and increased in the U17 age group.

- There was no significant difference between the relative leg stiffness data recorded on two separate testing days and a high average intraclass correlation coefficient was reported for the trial to trial reliability of the leg stiffness jump protocol.

- A significant time by group interaction effect for relative leg stiffness indicated a slight decrease in the U13 age group, no change in the U15's and a significant increase in the U17 age group post fatigue.

- EMD was significantly longer post fatigue in all age groups but the change from pre to post fatigue was greatest in the U13 age group.

CHAPTER V

DISCUSSION

5.1 Over-view of main findings

As this is the first known study to investigate the effect of football specific fatigue following simulated game play, on the dynamic knee stability in elite female youth football players. The findings provide practitioners with valuable information and form a starting point for future research. In addition to this, the study has raised important methodological issues in the determination of the FH/Q ratio which should be taken in to account in future projects.

The findings of this study have reinforced the importance of using angle specific averages to calculate the FH/Q ratio as the negative effects of fatigue on elite female youth football players was evident closer towards full knee extension but disappear as the knee flexes. These findings have important implications when investigating dynamic knee stability in this population as the ability of the muscular system to adequately stabilise the knee was impaired when fatigue was present but only near full knee extension. Furthermore, the findings have specific implications for female athletes who tend to land with the knee in more extended positions (Lephart et al., 2002). Future studies should therefore take this into consideration when calculating the FH/Q ratio and opt to use angle-specific average torque data to truly represent knee joint function.

The findings of the current study suggest that there are no detrimental effects on the muscular stability of the knee (FH/Q ratio) following a football specific fatiguing task irrespective of age group. This therefore suggests that other mechanisms other than muscular stability are predominantly responsible for the increased relative risk of knee injury in female youth football players when fatigue is present. This assumption was supported by the neuromuscular data collected in the current study.

Age effects in feed-forward pre-activation mechanisms were highlighted in the leg stiffness data when fatigue was present. Pre-pubertal players (U13) feed-forward mechanisms slightly decrease, pubertal aged players (15) remained similar and post-pubertal age players (U17) showed an increase post fatigue. This relative leg stiffness data may demonstrate an age effect in the development of feed-forward mechanisms with age and maturation or it could demonstrate the effectiveness of football specific training in the development of feed-forward mechanisms and pre-activation found in the older age group post fatigue. It is also a possibility that this increased feed-forward mechanism is a compensatory mechanism for the reduced ability to utilise neuromuscular feedback mechanisms when fatigued. However further research is required using non trained control groups in order to establish if this is merely a change through normal growth and maturation.

A significant increase in the EMD post fatigue highlighted that in female youth football players, neuromuscular feedback is impaired following a football specific simulated fatigue protocol irrespective of age. This effect is greater in younger and less mature girls and reduces with age, maturation and training. The age related changes in the findings with regards to the responses of both the muscular and neuromuscular feed-forward and feedback mechanisms to cope with fatigue may be related to a growth/maturational effect and/or training effect and require further investigation using non-trained controls.

This research is the first of its kind to demonstrate that football specific fatigue has a detrimental effect on the neuromuscular functioning of the muscles that support the knee in elite female youth football players. However, whether this response is accountable for the increased relative risk of injury in this population is unknown as the study only included females in the sample and therefore a comparison of the fatigue effects between females and males is unknown and requires future research. The reduced neuromuscular functioning in both the feed-forward and feedback mechanisms in the youngest age group may potentially be a protective mechanism for their relatively immature musculoskeletal systems. The U15 age group was the only group to show a decrease in both the FH/Q ratio (muscular) as well as a reduced EMD (neuromuscular) following fatigue and may therefore be considered a high risk injury group. The oldest age group appears to show signs of a possible compensation mechanism to protect the joint despite significant impairment to feedback mechanisms. Both muscular stability (FH/Q ratio) and feed-forward mechanisms (Leg stiffness) were increased post fatigue, possibly in order to protect the joint from the significant impairment to feedback mechanisms (EMD) when fatigue is present. The findings reinforce the importance of introducing training programmes to improve neuromuscular functioning and reduce the relative risk of injury (Hewett, 2000, Myer et al., 2008) in this at risk population. Additionally, the findings suggest that this neuromuscular training should be age/maturation specific as well as being undertaken in the middle/towards the end of training sessions in order to make it related to fatigue, which has not yet been previously prescribed.

5.2 Influence of football specific fatigue on FH/Q ratio

Both the hamstrings and quadriceps muscles are crucial for knee joint stability (Hughes and Watkins, 2006) and with the nature of agonist/antagonist muscle groups working together across a joint (Osternig, 2000), it makes studying this relationship paramount. Furthermore, the H/Q muscle strength ratio provides information on the functional stability of the knee by providing information on muscle balance around the knee joint (Baltzopoulos and Brodie, 1989). The ratio is frequently reported and important to practitioners due to the negative implications of a muscular strength imbalance on specifically the ACL and hamstrings (Holcomb et al., 2007). Vigorous quadriceps muscle action unopposed by antagonist hamstring recruitment may elicit increased ACL strain and increase injury risk (Padua et al., 2006). Therefore, one of the aims of the current investigation was to examine the effects of football specific fatigue on the FH/Q ratio.

In order to increase the functional relevance of the study, the FH/Q ratio was calculated using angle specific average torque values and tested over a range of angular velocities. Following statistical analysis, a significant time by joint angle interaction was found indicating that regardless of age or velocity, the FH/Q ratio at the most extended joint position (0-10° of knee flexion) decreased post-fatigue compared with pre-fatigue. Furthermore, as the knee was further flexed, this negative effect of fatigue disappeared and by 20-30° of knee flexion the FH/Q ratio showed an increase post-fatigue. With the identification that near full knee extension static stability is reduced and functional stability relies on the dynamic stabilisers to protect the knee (Griffin et al., 2006) coupled with the fact an ACL rupture is most likely to occur near full knee extension during high velocity movements (Renstrom et al., 2008) importance is placed on these findings. The data from the current study highlights the influence fatigue has on muscular dynamic knee stability and that this influence is angle specific, therefore reinforcing the inappropriate use of PT to calculate the FH/Q ratio. Epidemiological data often reports that injury is more frequent in the latter stages of football matches when fatigue is present and after numerous repetitions of the same movement (Hawkins et al., 2001, Ostenberg and Roos, 2000, Olsen et al., 2004). This finding suggests that muscular stability systems are affected by changes in knee joint angles in elite female youth football players. This mechanism may be related to the force-length relationship and disruption through muscle damaged causing a shift to optimum force production at longer muscle lengths and less force production at shorter muscle lengths (Wilmore et al., 2008). Thus, by analysing the angle specific data pre and post fatigue, it became evident that in female youth football players, eccentric muscle actions are less effective when in extended knee positions when fatigue is present. Following a bout of football specific fatigue, the ability of the hamstrings to act eccentrically to counteract the concentric quadriceps is diminished, resulting in a decrease in the ratio. These findings are of particular importance for football players who during games and training frequently place the knee in extended positions in common movements such as kicking, twisting, pivoting and landing. Research on landing mechanics in female athletes indicated that females tend to land with a greater knee extensor moment, thus landing with the knee in a more extended position (Hass et al., 2005, Lephart et al., 2002) rather than absorbing the impact with knee flexion (Lephart et al., 2002). This landing technique displayed by females with the knee extended makes them vulnerable for ACL loading and therefore at risk of rupture (Lephart et al., 2002). These findings along with the results reported in the current study propose that landing in a more extended position towards the end of a football match when fatigue is present may increase the relative risk of sustaining an injury in this at risk population group.

As this is the first study to have examined the FH/Q ratio based on angle specific averages in female youth football player's pre and post fatigue, it is difficult to compare the findings to previous literature. There is also limited adult data using angle specific data available therefore further making comparison difficult.

Available studies on adult football players have reported a significant reduction in the FH/Q ratio using PT following fatiguing exercise (Small et al., 2010, Rahnama et al., 2003, Delextrat et al., 2011). These studies have induced fatigue in various ways such as on a laboratory treadmill (Rahnama et al., 2003) or by using field based protocols (Delextrat et al., 2011, Small et al., 2010) and have also determined torque with the hip in a flexed position which is not functionally relevant. There currently appears to be no published studies that have explored the influence of fatigue on angle specific FH/Q ratios other than unpublished data which has reported that the angle specific FH/Q ratio determined with a functionally relevant extended hip position, increases closer to knee extension when fatigue is present in adult participants (*n*=110)(Elnagar, 2012). This fatigue effect is a possible compensatory mechanism that by increasing the FH/Q ratio when fatigue is present is a way to respond to the reduced neuromuscular functioning (longer EMD) also caused by fatigue. This then provides the joint with some form of muscular protection. This is in contrast to the current study's findings which may therefore suggest that young girl's immature and developing muscular system is not advanced enough to compensate for the compromised neuromuscular effects of fatigue (see section 5.4). This is highlighted with the lack of ability of the hamstrings to act eccentrically close to full extension when fatigue is present thus resulting in a decrease in the FH/Q ratio.

The significant main effect for joint angle in the current study indicated that the FH/Q ratio was higher between 10-20° than at both 0-10° and 20-30° of knee flexion. No significant difference was evident between 0-10° and 20-30° of knee flexion. This is in contrast to the adult literature which reports an increase in the FH/Q ratio as the knee approaches full extension (Aagaard et al., 1998, Coombs and Garbutt, 2002, Elnagar, 2012). This protective mechanism of an increase in the FH/Q ratio as the knee moves towards full extension is due to a larger decrease in concentric quadriceps torque than eccentric hamstring torque. Thus, the joint is some-what stabilised as the hamstring torque counteracts the torque produced by the quadriceps to reduce the anterior tibial sheer force placed on the ACL. The data in the current study does not show this muscular protective mechanism and therefore suggests that female youth football players may be at risk during movements that extend the knee. The mechanisms behind this proposed adult/child angle specific difference are difficult to prescribe but could be related to either a) age/ maturational effects of eccentric torque production; b) quadriceps dominance in females; c) football specific training muscular effects and/or d) a combination of these factors. In the current study it is unlikely that the first hypothesis is true given the post-pubertal status of the U17 participants. However, whether there are protective mechanisms acting on the younger age groups to reduce muscle lengthening in order to limit eccentric torque production when the knee joint is almost fully extended (0-10° of knee flexion) remains to be investigated. It is also unlikely that the second hypothesis is true given that in adults, there was no angle related difference between male and female participants (Elnagar, 2012). Nevertheless, whether quadriceps dominance is evident in the female youth footballers in the current study is an interesting point and it is possible that the conflicting findings of the effect of joint angle on FH/Q ratio are related to sport specific muscular effects of traditional football training. Recent work on male youth football players (15 year-olds) has reported that loading patterns experienced during traditional football training asymmetrically strengthen the muscles about the knee, altering the balance towards more of a quadriceps dominance (Iga et al., 2009). This research by Iga et al. (2009) demonstrated a significant training effect in male youth footballers using PT to calculate FH/Q ratio, with lower ratios reported in conventionally trained players (technical and tactical training with game related fitness elements) compared with resistance trained footballers and controls. As the female football players complete the same volume of training per week (2 x 2 hour training; 1 competitive match) to the male players in this study and also follow a conventional training schedule, this hypothesis could be possible but requires further investigation.

If traditional football training in female youth football players produces quadriceps dominant players, then we would expect to see significant age effects in the current study as the older age groups would have had more exposure to traditional football training. This however was not the case; no significant age differences were found in the FH/Q ratio between the U13, U15 and U17 age groups. This is in contrast to the cross-sectional study on a large group of male youth football players (*n* =157) aged from 12-18 years (Forbes et al., 2009). Forbes et al. (2009) reported significantly lower FH/Q ratios in the U18 age group compared with the U12 age group (0.84 versus 1.01 respectively). This reduction in the ratio with age was due to a greater increase in concentric quadriceps torque compared to eccentric hamstring torque, reinforcing the hypothesis that traditional football training develops quadriceps dominance in males (Iga et al., 2009). It is possible that this may reflect an interaction of sex and maturation as well as training. As boys hit maturation they increase anabolic androgens and increase muscle mass (Wilmore et al., 2008) which may be exaggerated further in response to training. This effect may not be observed in females due to different maturation processes. Furthermore, in contrast to the results of the current study are the findings of an investigation using non-trained male and female children, teenagers and adults to investigate the age and sex associated changes in the FH/Q ratio (De Ste Croix et al., 2007). A significant difference was reported with the prepubertal children producing a significantly lower FH/Q ratio than both the teenagers and adults (0.97 versus 1.23 versus 1.19 respectively) at 180°/s. Despite these conflicting reports, the results of the current study are in agreement to the work of Gerodimos et al. (2003) who found no significant age effects when investigating the FH/Q ratio in young basketball players aged 12-17. Direct comparisons between the results of these studies and the results of the current study are difficult to make due to the variety of methods followed. For example, the studies previously cited have determined the FH/Q ratio using PT and tested with the participants in a seated position with the hip flexed, both of which lack functional relevance as they do not represent knee joint function in sporting situations. The hip position is important when assessing torque values on isokinetic dynamometers as research has shown there to be a significantly greater torque production when sitting compared to when in prone/supine (Black et al., 1993). A recent study indicated that seated torque was significantly greater than supine torque in rugby players, highlighting that hip angle influences both concentric and eccentric PT (Deighan et al., 2012). Furthermore, comparisons between the torque generated in prone and supine have been made, highlighting a significant difference, with torque recorded in the prone position greater than in supine (Worrell et al., 1990). Therefore caution should be taken when comparing studies using different hip positions.

The results of the current study show no main effect of time on the FH/Q ratio and a possible explanation for this could be related to the football specific fatigue protocol used. Various football specific protocols are available but generally field based protocols such as the LIST (Nicholas et al., 2000) or the SAFT^{90} (Small et al.,

2010) are favored due to the greater ecological validity than a treadmill based protocol as they are more representative of movement patterns involved in a match (Delextrat et al., 2011). As the LIST protocol includes a run to exhaustion aspect at the end of the task, the $SAFT^{90}$ was deemed more appropriate. This said a possible explanation for the lack of any significant effects of time/fatigue could be due to the limited eccentric actions in the $SAFT^{90}$. The protocol does contain periods of rapid deceleration and some subtle cutting and direction changes however the negotiation through the poles in the course is limited to a swerve rather than a true cutting movement. Additionally, as the protocol does not include any jumping, landing and kicking movements which are actions that place a greater stress on the eccentric portion of the muscle the hamstrings may not have been worked as much as they are in a game. In order to cater for the eccentric work of these game specific actions, a protocol integrating jumping, landing and kicking actions as well as rapid deceleration and direction changes would be valuable. It should also be noted that the $SAFT^{90}$ is based on English Championship men's football and the activity profile may be different in female youth football. Although logistically more difficult, ideally it would be beneficially to explore the FH/Q ratio following a competitive fixture in order to collect valid data which fully represented the muscular and neuromuscular response to football specific fatigue.

No statistically significant group by time interaction effects on the FH/Q ratio were reported in the current study. However, age related data approached statistical significance ($F_{2,34}$ = 2.299, p = 0.07) and age group associated differences from pre to post fatigue can be observed in the FH/Q ratio data. It is therefore possible that with a larger group size the age related data would reach statistical significance. From pre to post fatigue, the U13 age group remained similar (5.8% increase) the U15 age group decreased (15.8% decrease) and U17 age group increased (17% increase). The absolute difference in the FH/Q ratio between the U15 and U17 age group from pre to post fatigue is 0.51. This difference in the fatigue related response to dynamic muscular stability in female youth football players clearly has some practical significance and may have reached statistically significance with a large sample size. Previous adult literature has reported conflicting findings to the non-significant main effect for time reported in the current study (Delextrat et al., 2011, Small et al., 2010, Rahnama et al., 2003). All of these studies are consistent in reporting that the eccentric hamstring torque decreased to a greater extent than the concentric quadriceps torque when fatigue was present. However, the results of these studies should be taken with a degree of caution as they all use PT to calculate FH/Q ratio and all tested with the hip in a flexed position, both which lack functional relevance.

It is relatively difficult to prescribe the current study's findings to physiological and biomechanical mechanisms as well as compare them to previous literature as this is the first study to have explored the effect of football specific fatigue on the FH/Q ratio in female youth football players using averaged angle-specific data. In support of the U17 findings of increased FH/Q ratio when fatigue is present, the study of Wright et al. (2009) reported a significant increase in the FH/Q ratio following fatigue (0.88 versus 1.08). The protocol used by Wright et al. (2009) to induce fatigue consisted of 50 maximal concentric knee flexion/extension repetitions and was conducted on recreational football players (n = 8). EMG analysis also identified that the co-activation of the hamstrings during the concentric quadriceps muscle action increased post fatigue. This increase in hamstring co-activation following fatigue is suggested as a way to increase joint stability in order to act as a safety mechanism during knee extension (Wright et al., 2009) and may be attributed to the greater FH/Q ratio found in the U17 age group in the current study. As previously highlighted, comparable data from youth football players is limited however unpublished work has explored football specific fatigue; induced by the SAFT^{90}, on angle specific FH/Q ratio in U18 male professional footballers (n = 15) (Davenport, 2011). This investigation found no significant change in the FH/Q ratio post fatigue irrespective of joint angle or movement velocity. It should be noted that every players FH/Q ratio did increase (some more than others) just not significantly and may support the hypothesis that the SAFT^{90} may not include enough eccentric work. The available data on male footballers and the current studies U17's data suggest that the FH/Q ratio is not compromised following football specific fatigue. Furthermore, the current study suggests that post puberty muscular stability is increased when fatigue is present in female youth football players. However, an unchanged ratio but with lower levels of absolute torque may also represent reduced stability and highlight the importance of looking at the hamstring and quadriceps torque data as well as the FH/Q ratio. It is difficult to prescribe mechanisms for this post fatigue increase in FH/Q ratio but it is due to the greater reduction in concentric quadriceps torque production post fatigue compared with the decline in eccentric hamstring torque production. Previous research has identified that eccentric muscle actions are generally more fatigue resistant than concentric muscle actions (Roig et al., 2009). Additionally, sex differences in muscle fatigue exist with females displaying a greater relative fatigue resistance than males during repeated high-intensity tasks (Hicks et al., 2001). These are possible explanations for the difference in findings of the present study and the significant decrease in the FH/Q ratio previously reported in football fatigue related studies that have used adult males as participants (Small et al., 2010, Rahnama et al., 2003). The findings of the current study suggest that there may be a development of fatigue resistance following repeated eccentric muscle actions with maturation in young girls towards the adult state (U17). Another possible suggestion based on the findings in U18 male professional players (Davenport, 2011) is that there may be an additional protective mechanism which is developed through football training and total hours of exposure, preventing a detrimental effect of fatigue on FH/Q ratio. However, this idea requires further investigation by exploring whether the fatigue related effects reported in the current study are present in non-trained young girls. The increase in the FH/Q ratio post fatigue observed in the U17 age group is possibly related to both maturational and training status in order to protect the joint following the detrimental effect of fatigue on neuromuscular stability (see section 5.4).

It is well recognised within adult literature that fatigue effects concentric and eccentric actions differently. Generally speaking, eccentric muscle actions are more susceptible to muscle damage than concentric muscle actions (Roig et al., 2009) and this may be the most important type of fatigue from an injury perspective. Following on from this, in a fatigued state the FH/Q ratio should increase making the knee more stable as found in the U17 age group of this study. However, a significant decrease in the FH/Q ratio was found in the U15 age group and these findings are comparable to previous adult findings (Oliveira et al., 2009, Delextrat et al., 2011, Rahnama et al., 2003, Small et al., 2010). All these studies are consistent in reporting a greater decrease in eccentric hamstring PT compared to concentric quadriceps PT and suggest the stability of the knee joint is compromised during forceful knee extension movements when fatigue is present. However, the mechanisms associated with this decrease in the ratio in the U15 age group are more difficult to prescribe than adults and are possibly related to the pubertal status of the group. The decrease in FH/Q ratio in pubertal female football players is an interesting finding as we observed similar pre and post FH/Q ratio in the U13 pre-pubertal age group which then switched to a decrease in the ratio in the U15 pubertal group and then an increase in the ratio in the U17 post-pubertal group, which suggests the changes are possibly due to changes in development and metabolic specialisation. It has been suggested that pre-pubescent children appear to be metabolic non-specialists, meaning that they are neither classified as anaerobic or aerobic performers (Bar-Or and Rowland, 2004). Available information suggests that that there is a progressive rise in anaerobic glycolysis as children age and a reciprocal decline in aerobic metabolism capacity, which contributes to alterations in exercise fatigue (Rowland, 2005). Therefore, it is possible that the participants in the U15 age group in the current study are in the transition from being non-specialists like the U13's to becoming specialists like the U17's. Furthermore, this age group may be moving from relying on aerobic sources to generate energy to using predominantly anaerobic sources and not yet developed metabolic strategies to cope with the by-products of this process unlike the post-pubescent U17 age group, which would explain the negative muscular response to fatigue shown in this age group compared to the positive response in the U17 age group. In support of this theory is evidence that young children are more fatigue resistant than adults (De Ste Croix et al., 2009, Ratel et al., 2006) due to: a) quicker use of oxidative pathways that lead to a lower accumulation of by-products, b) the lower ability to activate type II muscle fibres, c) and the possibility of faster phosophocreatine resynthesis, improved acid base regulation and faster removal of metabolic by-products (De Ste Croix and Deighan, 2012). Additionally, it is suggested that for girls, PHV occurs at approximately 12 years of age with peak weight velocity (PWV) occurring at approximately 12.5 years (Kenney et al., 2011). Therefore, it is possible that the U15 players' data; who were on average 1 years post PHV, is related to the rapid change in body weight (PWV) during this pubertal stage and the increased likelihood of injury due to increased loading. Potentially, the U15 players are experiencing increases in fat mass which provides an additional load for them to carry and increases ground contact loading (Wilmore et al., 2008). Another explanation is that there could be a protective mechanism in the U15 age group that does not allow them to develop large eccentric force in the hamstrings when fatigued as a way to protect the joint. This avoidance of extensive muscle lengthening in order to prevent muscle damage would be seen as a protective mechanism, however in this situation it is an unwanted effect as it potentially increases the relative risk of injury by decreasing knee joint stability. All of the suggestions for the findings in the current study are initial explanations and therefore require further investigation.

It should be noted that a further explanation of the negative fatigue effect seen in the U15 age group compared with the U17 age group could surround the completion of the football specific fatiguing task. The SAFT^{90} protocol is based on participant self regulation and workload is not matched or monitored so it could simply be that the U15 age group worked harder than the U17 age group and therefore induced a greater fatigue response. This hypothesis is partly supported by the data we collected for descriptive and feedback purposes on the distance travelled during the simulated game. The mean difference between the mean distance covered by the U15 and U17 age groups during the SAFT^{90} was only 65m (10,525m versus 10,590m) despite the U15 participants performing for 10 minutes less than the U17 participants (80 versus 90 minutes).

It would appear that the reduced muscular stability alongside the reduced neuromuscular stability (see section 5.4) following football specific fatigue seen in the current study places the pubertal female football player at the greatest risk of knee injury. It is therefore relevant to mention that the reason why the U15 age group had a smaller sample (n = 9) than both the U13 (n = 14) and U17 (n = 13) age groups was because four players in the U15 age group were suffering with knee injuries during the testing period. The findings of the current study placing pubertal players at the greatest risk of injury is supported by recent football injury incidence data on boys and girls in the development years (6-18 years) that reported a significant increase in injury incidence from 9-12 year olds (8.0 injuries/1000h of exposure) compared to 13-16 year olds (65.8 injuries/1000h of exposure) (Rumpf and Cronin, 2012). There may be a variety of changes in the body in the U15 age group such as moving to metabolic specialization (Bar-Or and Rowland, 2004), increased fat mass and anatomical changes (Wilmore et al., 2008) all with consequences on neuromuscular control. This incidence data further highlights the injury risks associated with this age group and shows the importance of introducing prevention programs to target muscular and neuromuscular factors at an early age that are age group specific.

5.3 Influence of football specific fatigue on relative leg stiffness

Leg stiffness has an important role in the dynamic stability of the knee and without adequate stiffness a person may be at risk of injury (Hughes and Watkins, 2006). Feed-forward mechanisms prepare the joint before ground contact (Ford et al., 2011) with this pre-activation allowing force absorption and as a result decreases stress on ligaments (Hewett et al., 2005) and is therefore an important part of neuromuscular control. It is difficult to compare the findings of the current study to previous literature as this was the first study to have explored the effect of football specific fatigue on relative leg stiffness in female youth football players.

The current study revealed a significant time by group interaction effect which was due to a slight decrease in relative leg stiffness in the U13 age group, no change in the U15 age group and an increase in the U17 age group pre to post fatigue. These results suggest that football specific fatigue induces an inhibitory response in younger pre-pubertal players and an excitatory response in older post-pubescent players. The observed increase in leg stiffness in the older age group suggests a shift to increased prepatory muscle activation which will stiffen the joint prior to landing thus, decreasing the stress on the knee joint and reduce the risk of knee injury (Hewett et al., 2005) upon landing and when fatigued. In contrast, the reduced pre-activation in the younger age group is due to more of a yielding action and less efficient movement (Wilson and Flanagan, 2008), which will decrease stability and potentially increase the risk of ACL injury (Padua et al., 2005) when landing and fatigued. Data was also collected to explore the inter and intra session reliability of the method used to collect the leg stiffness data as it had previously only been used on young boys (Lloyd et al., 2009). Similarly to the previous authors, a high average intra-class correlation coefficient was reported for the trial-to-trial reliability of the four repetitions, suggesting a strong correlation between trials. Statistical analysis revealed no significant difference in inter-session reliability, suggesting that using mobile contact mats is a reliable field-based method when examining leg stiffness between sessions in young girls.

Available adult data is conflicting as some studies have shown an increase in stiffness post fatigue (Morin et al., 2011), some show no change in stiffness (Girard et al., 2011) and some show a decrease in stiffness (Dutto and Smith, 2002). Due to differences in the protocol used to induce fatigue and the different methods used to calculate stiffness, it is difficult to attribute these findings to mechanistic structures. Limited leg stiffness data on children when fatigued is available, however unpublished data on 16 year old boys has shown an individual response of leg stiffness following 45 minutes of football specific exercise (Oliver, 2008). Furthermore, Hunter and Smith (2007) concluded that the effect of fatigue on leg stiffness is subject specific/individualised as some participants increased stiffness, some decreased while others showed no change post fatigue. Therefore differences in findings post fatigue may be due to this individual response. Caution should be taken when comparing the results of studies exploring leg stiffness as research has highlighted that stiffness is related to the speed of the movement (Oliver and Smith, 2010). It is also important that when exploring age/ maturational related differences in leg stiffness that both body mass and limb length are taken into consideration due to their mechanical influence on the movement (McMahon and Cheng, 1990). This is especially important when comparing children of different ages/maturational stages where proportional changes in limb length during growth and maturation play a key role in biomechanical and muscular functioning. The relative leg stiffness value reported in the current study took into account both of these factors, however previously limb length is often ignored.

The pre fatigue stiffness values of the U13 and U15 age groups in the current study are similar to the values previously reported using the same protocol in young boys (Lloyd et al., 2012, Oliver and Smith, 2010). Lloyd et al. (2012) reported similar relative leg stiffness values in 12 year olds (43.53 ± 13) and 15 year olds (49.50 ± 12.17) to the pre fatigue data collected for the current studies U13 (44.6 ± 5.5) and U15 (46.4 ± 8.8) age groups. Oliver and Smith (2010) reported relative leg stiffness at three hopping frequencies of 1.5Hz, a self selected preferred frequency and at 3.0Hz in 11-12 year old boys. The relative stiffness values were 15.1 ± 5, 22.0 ± 9.2 and 51.6 ± 5.1 respectively, identifying the speed of the movement to be an important factor in leg stiffness results. The authors also tested adult males and reported that significant age related effects in the neural control of leg stiffness are present in boys, with stiffness increasing with age. This significant age effect was also present in the study by Lloyd et al. (2012) with leg stiffness increasing from 9 to 12 year olds and greatest in 15 year old boys when compared to the younger ages. The current study also displayed age related differences in relative leg stiffness, however this difference did not increase with age; it in fact decreased, with the U17 age group displaying lower values pre fatigue than both the U15 and U13 age groups. This difference is difficult to explain as it has been proposed that in young boys there is a clear maturational effect on leg stiffness that is related to growth and the development of motor control (Lloyd et al., 2012). Lloyd et al. (2012) suggest that as children mature they become more reliant on supra-spinal feed-forward mechanisms to regulate greater levels of leg stiffness. However, it is again possible that the results in the current study reflect an interaction of sex and maturation. Boys display greater changes in muscle structure and function than girls throughout maturation, with girls increasing fat mass (Wilmore et al., 2008), therefore normalising to body mass may disadvantage the older and more mature players. The current study is in agreement with this concept in female youth football players; however only when fatigue is present. It is therefore likely that the age related effects in the female football players in the current study are purely due to the effects of fatigue rather than from normal growth and maturation. There is supporting data that has also demonstrated no significant maturation effects in leg stiffness once absolute stiffness was normalised for body mass in 11-13 and 16-18 year olds during a hopping task (Korff et al., 2009).

The U13 relative leg stiffness data; which shows a small decrease from pre to post fatigue, suggests a detrimental effect of fatigue on neuromuscular feed-forward mechanisms and immediate stretch-reflexes in pre-pubertal female youth footballers. It is also important to report that there were no individualised effects of fatigue on leg stiffness with all participants decreasing following the fatigue task. This reduction in feed-forward mechanisms indicates longer ground contact times, shorter flight times and a likely shift in the neural control to a lower contribution from pre-activation and short latency stretch reflexes. The reason for this neural response in this age group is unclear but it could be related to a protective mechanism to prevent rapid overload of the relatively immature musculotendon system upon ground contact (Lloyd et al., 2012). It is well recognised in the literature that the Golgi complex is considerably diminished in size and number in adults compared with children (Oliver and Smith, 2010) and this could be responsible for the increased protective mechanism. The findings of the current study suggest that young female footballers (U13) ability to recall pre-programmed commands to regulate stiffness may not be optimal when fatigue if present.

The U15 relative leg stiffness data found in the current study is in agreement with a previous unpublished report on U16 male footballers that showed no significant change in relative leg stiffness following 45 minutes of football specific exercise (Oliver, 2008). Additionally, the Oliver (2008) data showed an individual response to the fatigue protocol with some individuals increasing leg stiffness post fatigue, while others decreased leg stiffness. This hypothesis of an individual response to fatigue is supported by the work Hunter and Smith (2007) on adults. The authors demonstrated that following a one hour exhaustive run some participants increased stiffness, some showed no change while others decreased. This individualised response to fatigue was present in the U15 age group in the current study, indicating that pre-activation was enhanced in some individuals but reduced in others post fatigue. The variation of either a slight increase or slight decrease in leg stiffness post fatigue shown in this group could be related to the pubertal status of the group, as the U15 age group contained individuals at differing stages of maturation (range in offset from PHV was +0.41 – 1.95 years). The U15 data of the current study suggest that female players who are progressing through puberty do not show a significant detrimental effect of fatigue on feed-forward neuromuscular mechanisms, however they also do not use feed-forward mechanisms in a compensatory manner, as shown in the U17 age group.

The data reported in the U17 age group shows participants to significantly increase relative leg stiffness when fatigued. This suggests there are enhanced feed-forward and stretch reflex mechanisms in post pubertal female footballers following a simulated game. Morin et al. (2011) investigated changes in running kinematics, kinetics and spring-mass behavior over a 24 hour run. The authors reported a significant increase in both leg and vertical stiffness following the fatigue protocol. The reason for this enhancement in the current study is difficult to explain, but it is possible that the increase is some form of compensatory mechanism; as with the increase in muscular stability (FH/Q ratio) post fatigue, to counteract the longer latency times (EMD) when fatigue is present. These findings suggest that either through normal growth and maturation and/or football specific training that post pubescent female football players compensate for the reduced feedback mechanisms (EMD) post fatigue by increasing muscular stability (FH/Q ratio) as well as increasing feed-forward mechanisms (stiffness) in order to protect the knee joint. Furthermore, the current study demonstrates a possible age effect in leg stiffness as the youngest age group decrease following fatigue where as the oldest age group increase. Lloyd et al. (2012) demonstrated significantly greater absolute and relative leg stiffness in 15 year olds compared to 12 and 9 year olds. Similarly, Oliver and Smith (2010) demonstrated that men were able to increase their feed-forward mechanisms as they demonstrated a greater relative stiffness compared to boys at faster hopping frequencies. These findings support the idea that there are age related effects on leg stiffness and therefore support the data in the current study; however this age effect is only evident when fatigue is present. Whether this age effect when fatigued in the current study is related to age and maturation, or is further enhanced through football specific training in female youth football players requires further investigation using non-trained controls. A further possible explanation for the increased leg stiffness post fatigue seen in the current study could be related to a training/learning effect and skill mastery. Laffaye et al. (2005) investigation on leg stiffness and expertise in men when jumping indicated that experts demonstrated an increased stiffness in order to maximise jump height compared to novices. It is therefore possible that the U17 participants in the current study have learned to increase stiffness when fatigued in order to maintain performance as well as help to reduce the relative risk of injury.

The relative leg stiffness data in the current study could potentially demonstrate some form of training effect which is greater than expected changes seen through normal growth and maturation. This however, would require further investigation using control groups in order to compare the findings to non-trained individuals. Limited data on the effect of training on leg stiffness in children is available, however a recent study has reported that leg stiffness was improved in 12 and 15 year old boys following 4 weeks of plyometric training (Lloyd et al., 2011). This study concluded that training can improve relative leg stiffness in children; however training may be age dependent as 9 year old participants in the same study did not improve. It is therefore possible that the change from an inhibitory effect of fatigue in the U13 age group to an excitatory response in the U17 age group is due to some form of training effect in which the ability to compensate for a reduction in another stability mechanism (in this case EMD) with fatigue is developed through training. Finally, it should be noted that none of the age groups in the current study had undergone any systematic plyometric, resistance or eccentric conditioning programmes, therefore any possible training effects are related purely to the traditional football specific training being completed.

5.4 Influence of football specific fatigue on EMD

Electromechanical delay can be defined as the latency between the onset of electrical activity in the muscle and the onset of force generation by that muscles contraction (Yavuz et al., 2010). It is classified as a characteristic of neuromuscular function (Blackburn et al., 2009) and is vital in sports performance as it affects the muscular response time to a stimulus. A vital part of the EMD of a muscle is the stretching of the series elastic component (SEC) as it has been suggested that the time required for the contractile component to stretch the SEC is responsible for the major portion of EMD (Zhou et al., 1996, Winter and Brookes, 1991).

The current study reported a significant time by group interaction and main effect for time and group for EMD, indicating that football specific fatigue significantly increases the EMD post fatigue in female youth football players. The data reported demonstrates that regardless of age, neuromuscular feedback mechanisms are significantly compromised during football performance in elite female youth football players. Furthermore, the youngest age group tested (U13) were the most affected, highlighting that the reduced ability of the neuromuscular system to contribute to knee stability when fatigued is most extreme in this age group. A significant main effect for time was found, indicating that the EMD of all three muscles assessed was longer following the fatigue protocol compared to before the fatigue task. It is suggested that this lengthening post fatigue which is frequently reported in the literature (Zhou et al., 1996, Yavuz et al., 2010, Howatson, 2010) is due to metabolic inhibition of the contractile process and excitation-contraction coupling failure; both suggested to explain peripheral fatigue (Kent Braun, 1999). Therefore, the findings of the current study suggest that there is a reduced capacity of the dynamic stabilisers of the knee to provide forceful corrective responses to mechanical loading of the knee using feedback mechanisms, when fatigue is present in female youth football players. This detrimental effect of fatigue and change in neuromuscular performance may represent an increased risk of injury. For example, research has identified that well-timed activation of the hamstring muscles; ACL synergists, can protect the ACL from mechanical strain by stabilising the tibia and reducing anterior tibial translation and highlights that it is the speed of this activation that is vital for the subsequent joint stability (Shultz and Perrin, 1999). Thus, when fatigued the female youth football players in the current study had a reduced ability to quickly activate their muscles following a stimulus to protect their joint from injury.

It is somewhat difficult to compare the findings of the current study to previous literature as to our knowledge this was the first study to examine the effect of fatigue on EMD changes during eccentric muscle actions of the hamstrings. Furthermore, no studies have examined the effect of football specific fatigue on EMD in elite female youth football players. Available unpublished work has shown a significant increase in EMD during eccentric hamstring exercise in both male and female adults, with the effects significantly greater in the female participants (Elnagar, 2012). These findings are in agreement with the findings of the current study indicating that EMD during eccentric hamstring actions are compromised when fatigue is present.

A number of adult studies have investigated the effect of fatigue on EMD; however this is mainly during isometric muscle actions. Previous literature identifies that EMD is influenced by; the type of muscle action (Cavanagh and Komi, 1979), joint angle (Grabiner, 1986), the effort level (Vos et al., 1991), fatigue (Nilsson et al., 1977) and the age and sex of the participants (Clarkson and Kroll, 1978). The majority of adult studies have shown that EMD significantly increases following a fatiguing bout of exercise (Nilsson et al., 1977, Zhou et al., 1996, Howatson, 2010, Elnagar, 2012). Nilsson et al. (1977) reported an increase in the EMD of the vastus lateralis muscle during concentric muscle actions. Following 100 maximal isokinetic knee extensions the EMD increased from 95ms at rest, to 115ms half way through the protocol and 121ms post fatigue (27% increase) in which the PT, work and power all decreased by approximately 50%. Similarly, Zhou et al. (1996)

reported an increase in the EMD of the knee extensors during isometric muscle actions following 30 seconds of all out sprint cycling. Following the fatiguing exercise, the EMD increased from 40 ms at rest, to 63 ms post exercise (57% increase). This EMD percentage change reported by Zhou et al. (1996) is very similar to that reported in the current study (57% versus 58%) despite differences in the muscle tested and muscles action performed. In contrast, the EMD percentage change reported by Nilsson et al. (1977) is smaller than reported by both Zhou et al. (1996) (27% versus 57%) and the current study (27% versus 58%), highlighting the influence different fatigue protocols and the age and sex of the participants can have on EMD. Howatson (2010) explored the impact of damaging exercise on EMD in the biceps brachii and revealed some interesting findings. The author reported that following fatiguing exercise, EMD remained compromised 96 hours following the task despite force production returning to pre fatigue levels. The author concluded that EMD was a useful tool for monitoring recovery following intense damaging exercise. The previous literature on adults have important implications for injury risk as neuromuscular feedback mechanisms appear to be compromised following fatigue and remain compromised even after muscular components have fully recovered. The chronic effects of football specific fatigue on EMD were not investigated in the current study. However, as the increase in EMD post fatigue was relatively large it is possible that female youth football player's neuromuscular feedback mechanisms remain compromised until their next training session; a few days later, which could place them at an increased relative risk of injury. This hypothesis requires further investigation exploring the chronic effects of football specific fatigue on both muscular and neuromuscular components on elite female youth football players. This data would give coaches vital information regarding the neuromuscular readiness to re-perform identifying an optimal time to train to avoid placing players at an increased relative risk of injury.

Currently there are no available paediatric studies that have explored the effect of fatigue on EMD in either boys or girls. The limited studies reporting EMD data on children have been exclusively on boys, during isometric actions and in a non-fatigued state (Cohen et al., 2010, Falk et al., 2009, Grosset et al., 2010, Zhou et al., 1995) therefore making comparison to the current study difficult. The work of Zhou et al. (Zhou et al., 1995) focused on the normal EMD range of the knee extensors as well as the effects of age and sex on EMD. The authors reported significantly longer EMD values in 8-12 year old children than in adults but no significant difference between EMD in the girls compared with the boys in the youngest age group (8-12 year olds). Similarly, Cohen et al. (2010) and Falk et al. (2009) found significantly longer EMD values in young boys compared with adult men. Differences such as lower muscle activation and lower muscle fibre conduction velocity in boys have been implicated in this longer EMD displayed in children (Halin et al., 2003) and may increase the potential for injury in children. It is suggested that children recruit and utilise less type II muscle fibres during maximal voluntary muscle actions than adults and therefore show a longer EMD (Falk et al., 2009, Halin et al., 2003). The data collected in the current study on the EMD of the hamstrings during eccentric muscle actions support this previously identified age related EMD difference. The U13 age group had a significantly longer EMD for all muscles tested (119 ms) compared with the U15 (93 ms) and U17 (92 ms) age groups which may be related to maturation changes in the muscle-tendon ability to generate and transmit force. These pre-fatigue EMD values are longer than those previously reported in the literature for isometric actions (Cohen et al., 2010, Falk et al., 2009, Grosset et al., 2010, Zhou et al., 1995) however this may be related to differences in the muscle group, muscle action and movement velocity tested. Additionally, it has previously been highlighted that EMD comparisons between studies is problematic as EMD values in adults have been seen to vary between 30 to 50 ms and up to a few hundred ms and vary depending on the muscle group, muscle action and movement velocity tested (Shultz and Perrin, 1999).

The current study is the first to demonstrate age related effects in the EMD of the eccentric hamstrings when fatigue is present in female youth football players. The significantly longer EMD both pre and post fatigue displayed by the U13 age group indicates a reduced ability of younger girls to quickly activate their muscles and respond to a physical (movement of lever arm) and visual stimulus (light box). One possible explanation for this is that younger girls may have a more compliant muscle-tendon system compared with older girls which requires more time to produce a mechanical response given the same stimulus. Another explanation for the age difference when fatigued in the present study could be due to the fibre type distribution, with type II fibres displaying shorter force-developing times compared to type I fibres (Winter and Brookes, 1991). Although muscle biopsy studies on children are sparse, the available literature indicates a decline in the percent of type I fibres from childhood to adolescence (Amrstrong and Fawkner, 2009) which may partly explain the results seen in the current study, however this hypothesis requires further investigation. Research by Cohen et al. (2010) identified that the level of training did not have any significant effect on EMD in 9-12 year olds, when comparing EMD of endurance trained and untrained children. The findings of the current study may challenge this lack of training effect and suggest that the number of total hours of athlete exposure may influence EMD by reducing the detrimental effects of fatigue as shown in the U17 compared with the U13 age groups. This hypothesis does however require further investigation exploring the fatigue effects on EMD using non trained participants in each age group.

It would appear that the prolongation of the EMD when fatigued found in the current study maybe largely attributed to a failure somewhere in the muscle contraction process as EMD has been shown to increase in parallel with muscle fatigue (Horita and Ishiko, 1987). This does not however explain the significant age effect reported in this study in the longer EMD both pre and post fatigue in the U13 age group when compared to the U15 and U17. As the time it takes to stretch the SEC forms a major part of EMD (Zhou et al., 1996, Winter and Brookes, 1991) the hypothesis that children have more elastic muscle and tendon which could increase the time required to stretch the SEC (Zhou et al., 1995) may account for these differences. The current study clearly displays an elongation of EMD with fatigue which is likely to reflect impaired contraction mechanisms. The mechanisms involved in this increased EMD following fatigue in female youth football players could be due to deterioration in muscle conductive, contractile or elastic properties and require further investigation.

The current study found no significant muscle specific differences in the EMD recorded pre or post the football specific fatigue protocol. Therefore, these findings suggest that during eccentric hamstring actions in female youth football players, there are no differences in the feedback mechanisms between the medial and lateral hamstrings or the calf muscles. Padua el al. (2006) suggested that when fatigued female athletes show an ankle-dominant strategy when landing, with a greater reliance on the ankle musculature and less on the knee musculature. This shift from knee dominance pre fatigue to ankle dominance post fatigue to stabilise the joint is suggested to occur as the ankle muscles tend to be less fatigued. This shift to less fatigued musculature was seen as a compensatory mechanism in order to maintain leg stiffness when fatigued (Padua et al., 2006). The current study appears to be the first to have examined changes in EMD pre and post football specific fatigue to explore if an ankle dominant strategy is evident in female youth football players. The current findings suggest that following football specific fatigue, female youth football players show no differences in the feedback response of the hamstrings or the calf. Furthermore, this suggests that female youth football players do not move towards an ankle dominant strategy when fatigue is present, irrespective of age, maturational status or training status. A limitation of the current study; as with Padua et al. (2006) is that the role of the gluteal muscles was not explored. It is possible that the fatigue protocol used may have altered the EMD of the gluteals in order to compensate for fatigue. Ethically it is difficult to explore the role of gluteals in female youth footballers but future research is necessary in order to investigate the effects of fatigue on the neuromuscular response of both the hip musculature and core muscles.

CHAPTER VI

APPLIED IMPLICATIONS AND RECOMMENDATIONS

The findings of the current study suggest that muscular functioning may not be dramatically impaired following football specific fatigue; however, it would appear that neuromuscular feedback mechanisms (EMD) are severely compromised in elite female youth football players regardless of age. Additionally, fatigue effects on leg stiffness appear to be age/maturation dependant and warrant further investigation. In addition to these main findings, various methodological issues have also been highlighted and should therefore be considered in future research. The findings of the current study have important implications and recommendations towards the ongoing effort to understand and prevent injuries in female football players.

The leg stiffness reliability data conducted as part of this project has highlighted the usefulness of mobile contact mats as a field collection tool. The sub maximal hopping task on mobile mats which was previously deemed reliable in young boys (Lloyd et al., 2009) is equally as reliable in elite female youth football players, whether this be within the same session (intra) or a separate session (inter). Moreover, the current findings relating to the FH/Q ratio propose that that muscular stability is negatively affected by fatigue near full knee extension. This finding reinforces the importance of using angle-specific average torque values to give a full picture of the stability of the knee joint when near full extension.

Injury incidence data has identified various mechanisms of ACL injury, highlighting that injuries commonly occur when the knee is close to full extension (Boden et al., 2000). Furthermore, it has been suggested that females tend to land in extended knee positions (Lephart et al., 2002). The results from the current study identified that once fatigued, the FH/Q ratio declines at 0-10° of knee extension while remaining similar at 10-20° and increasing at 20-30°. This decrease in muscular stability when fatigue is present places the participant at an increased relative risk of injury. Therefore any muscular conditioning prescribed to players should include and focus on movements towards full knee extension. In addition to this, training should focus at improving landing in the hope of preventing injury in female youth football players.

Previous investigations have indicated that the introduction of neuromuscular training programmes including; plyometrics, balance training, dynamic stabilisation training, eccentric training, trunk and hip training and static stretching reduce the relative risk of injury and enhance physical performance (Mandelbaum et al., 2005, Emery and Meeuwisse, 2010, Bizzini et al., 2012). However, these programmes have been solely introduced as warm ups; the effect of introducing these programmes towards the end of training sessions is unknown. It therefore seems necessary to introduce these programmes in the middle/ towards the end of a session in order to introduce and develop fatigue resistance to reduce the relative risk of injury associated with fatigue. EMD is shown to be drastically impaired post fatigue in all age group calling for an emphasis of intervention programmes to develop neuromuscular functioning. Given the detrimental effects on neuromuscular performance in all age groups following a football specific fatigue protocol in the current study, specific focus is needed on developing neuromuscular functioning in order to reduce relative injury risk.

The current study reported various age and maturation effects on the FH/Q ratio, leg stiffness and EMD. Age related differences in response to the fatigue task were present in muscular stability, with the U13 showing no change in the FH/Q ratio, the U15 showing a decrease and the U17 showing an increase. Moreover, the post fatigue leg stiffness data highlighted a slight decrease in the U13's compared to an increase in the U17 and an individualised response in the U15 age group with some players showing an increase while others showed a decrease. The EMD results highlighted that the U13 age group had a significantly longer EMD both pre and post fatigue when compared to the U15 and U17 age groups. These age group differences in response to fatigue require further investigation to establish if they were due to changes through normal growth and maturation or if they were related to the football specific training the participants took part in. Finally, it became evident that as female youth football players mature, they may use compensatory mechanisms in order to maintain knee joint stability when fatigue is present by increasing feed-forward mechanisms and muscular stability. How football specific training may contribute to this compensatory mechanism remains unknown and requires further investigation using non-trained controls.

The current study has provided useful cross sectional data on female youth football players in which there is a gap in the literature. However, future training studies are needed in order to design conditioning programmes that specifically target neuromuscular functioning. Therefore, the findings of the current study suggest that the following need to be considered in the further development of neuromuscular conditioning injury prevention programmes for elite female youth football players:

1. That muscular conditioning includes and focuses on the portion of the movement that is towards full knee extension and includes training aimed at improving landing performance.
2. That neuromuscular conditioning programme's are focused on being fatigue resistant and therefore undertaken in the middle or towards the end of training sessions rather than solely in warm ups.
3. That the primary goal of training programmes is focussed on enhancing neuromuscular functioning, with the secondary goal of improving torque production.
4. That training is age group and maturational stage specific and that specific neuromuscular training should be recommended, implemented and developed as early as possible.
5. That training during puberty is enhanced and individualised to focus on both muscular and neuromuscular aspects.
6. That training in younger pre-pubescent age groups focuses on the development and enhancement of feed-forward mechanisms in response to fatigue.

CHAPTER VII

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The current study has provided some unique and interesting findings into the effects of football specific fatigue on dynamic knee stability in elite female youth football players. However, as previously mentioned this study is cross sectional in nature and although it has provided essential information in relation to age and maturation differences in female youth football players, longitudinal studies are now needed to further explore the effects of growth and maturation on dynamic knee stability. The findings of the current study have highlighted the need to examine both neuromuscular feed-forward and feedback mechanisms as the response to fatigue may be age and maturation dependant. Future studies should continue to examine a range of potential risk factors and focus their investigations on female youth football players as they are an at risk population with limited data available.

Due to the large detrimental effects of football specific fatigue on EMD reported in the current study, along with reports that EMD remains compromised in adults up to 92 hours after fatigue (Howatson, 2010), future studies should focus on examining the chronic effects of football specific exercise on both muscular and neuromuscular functioning in elite female youth football players. This readiness to re-perform would not only appear to effect performance but could possibly be associated with the increased relative risk of injury and therefore requires further investigation. Future studies would also benefit from testing players after competitive match play in order to fully explore the role of football specific fatigue; however this would restrict outcome measures to those that can be achieved using portable equipment such as portable contact mats and EMG.

There is a need to further examine the compensatory mechanisms suggested in the current study on a wider range of muscles that contribute to knee stability such as the hip and core muscles. This would allow practitioners to identify; as with adults, whether female youth football players move to a muscular strategy of using muscles that are less fatigued to provide the desired knee stability and protect the ACL.

Available data indicates that neuromuscular training appears to reduce the relative risk of injury and enhance physical performance in late adolescent females (Mandelbaum et al., 2005, Emery and Meeuwisse, 2010, Bizzini et al., 2012), however these programs are solely implemented in warm ups. The current study has identified the need to introduce injury prevention programmes towards the end of training sessions in order to introduce and develop fatigue resistance. Developing and implementing such programmes when fatigued as well as during warm ups may help to reduce the relative risk of injury and researchers should therefore look to focus investigations on this in order to determine their effectiveness.

The limitations of the current study surrounding the $SAFT^{90}$, specifically that the movement patterns and duration of movement intensity being based on male adult professional football warrants future research as there is currently no alternative protocol for female or youth players. Additionally, the $SAFT^{90}$ may not have induced enough eccentric work in order to show a change in the FH/Q ratio due to the protocol being a simulation and not incorporating jumping, landing and kicking movements. The development of a protocol including these movements is therefore required.

The current study is the first to investigate the effect of football specific fatigue on dynamic knee stability in female youth football players and has provided important initial findings. With the results indicating various age/maturation effect as well as possible football specific training effects, further research is warranted.

CHAPTER VIII

REFERENCES

AAGAARD, P., SIMONSEN, E. B., MAGNUSSON, S. P., LARSSON, B. & DYHRE-POULSEN, P. 1998. A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *American Journal of Sports Medicine,* 26**,** 231-237.

AGEL, J., PALMIERI-SMITH, R. M., DICK, R., WOJTYS, E. M. & MARSHALL, S. W. 2007. Descriptive Epidemiology of Collegiate Women's Volleyball Injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 Through 2003-2004. *Journal of Athletic Training,* 42**,** 295-302.

AHMAD, C. S., CLARK, A. M., HEILMANN, N., SCHOEB, J. S., GARDNER, T. R. & LEVINE, W. N. 2006. Effect of Gender and Maturity on Quadriceps-to-Hamstring Strength Ratio and Anterior Cruciate Ligament Laxity. *American Journal of Sports Medicine,* 34**,** 370-374.

ALENTORN-GELI, E., MYER, G. D., SILVERS, H. J., SAMITIER, G., ROMERO, D., LÃ¡ZARO-HARO, C. & CUGAT, R. N. 2009. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy,* 17**,** 705-729.

ALLEN, D. G., LAMB, G. D. & WESTERBLAD, H. 2008. Skeletal muscle fatigue: cellular mechanisms. *Physiological Reviews,* 88**,** 287-332.

AMRSTRONG, N. & FAWKNER, S. G. 2009. Exercise metabolism. *In:* ARMSTRONG, N. & VAN MECHELEN, W. (eds.) *Paediatric Exercise Science and Medicine* Oxford; UK: Oxford University Press.

ARENDT, E. & DICK, R. 1995. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *American Journal of Sports Medicine,* 23**,** 694-701.

BAHR, R. & KROSSHAUG, T. 2005. Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine,* 39**,** 324-329.

BALTZOPOULOS, V. & BRODIE, D. A. 1989. Isokinetic dynamometry: applications and limitations. *Sports Medicine,* 8**,** 101-116.

BAMAÇ, B., ÇOLAK, T., ÖZBEK, A., ÇOLAK, S., CINEL, Y. & YENIGÜN, Ö. 2008. Isokinetic Performance In Elite Volleyball And Basketball Players. *Kinesiology,* 40**,** 182-188.

BAR-OR, O. & ROWLAND, T. W. 2004. *Pediatric exercise medicine : from physiologic principles to health,* Champaign, IL, Human Kinetics.

BASMAJIAN, J. V. & DE LUCA, C. J. 1967. *Muscles alive : their functions revealed by electromyography,* Baltimore, Williams & Wilkins.

BELL, D. G. & JACOBS, I. 1986. Electro-mechanical response times and rate of force development in males and females. *Medicine And Science In Sports And Exercise,* 18**,** 31-36.

BIZZINI, M., JUNGE, A. & DVORAK, J. 2012. Worldwide implemention of the 11+ injury prevention programme. *In:* ROI, G. S. & DELLA VILLA, S. (eds.) *Football Medicine Strategies for Knee Injury: International conference on sports rehabilitation and traumatology, Stamford Bridge Stadium, Chelsea FC, London.* Torgiano: Italy: Calzetti Mariucci Editori.

BLACK, S. J., WOODHOUSE, M. L., SUTTMILLER, S. & SHALL, L. 1993. Influence of hip position on electromyographic and torque productions in the knee. *J Sport Rehabil,* 2**,** 26-34.

BLACKBURN, J. T., BELL, D. R., NORCROSS, M. F., HUDSON, J. D. & ENGSTROM, L. A. 2009. Comparison of hamstring neuromechanical properties between healthy males and females and the influence of musculotendinous stiffness. *Journal Of Electromyography And Kinesiology,* 19**,** e362-e369.

BLAZEVICH, A., WAUGH, C. & KORFF, T. 2012. Development of musculoskeletal stiffness. *In:* DE STE CROIX, M. & KORFF, T. (eds.) *Paediatric biomechanics and motor control : theory and application.* London; New York: Routledge.

BLIMKIE, J. R. & MACAULEY, D. (eds.) 2000. *Muscle Strength,* Oxford: Oxford University Press.

BODEN, B. P., DEAN, G. S., FEAGIN, J. A., JR. & GARRETT, W. E., JR. 2000. Mechanisms of anterior cruciate ligament injury. *Orthopedics,* 23**,** 573-578.

BOLLEN, S. 2000. Epidemiology of knee injuries: diagnosis and triage. *British Journal Of Sports Medicine,* 34**,** 227-228.

BROER, M. R. & HOUTZ, S. J. 1967. *Patterns of muscular activity in selected sports skills; an electromyographic study,* Springfield, Ill., Thomas.

BRUGHELLI, M. & CRONIN, J. 2008. A review of research on the mechanical stiffness in running and jumping: methodology and implications. *Scandinavian Journal of Medicine & Science in Sports,* 18**,** 417-426.

BUTLER, R. J., CROWELL III, H. P. & DAVIS, I. M. C. 2003. Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics,* 18**,** 511-517.

CAMARDA, S. R. A. & DENADAI, B. S. 2011. Does muscle imbalance affect fatigue after soccer specific intermittent protocol? *Journal of Science and Medicine in Sport*.

CAVANAGH, P. R. & KOMI, P. V. 1979. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *European Journal Of Applied Physiology And Occupational Physiology,* 42**,** 159-163.

CHEATHAM, S. A. & JOHNSON, D. L. 2010. Anatomic Revision ACL Reconstruction. *Sports Medicine & Arthroscopy Review,* 18**,** 33-39.

CLARKSON, P. M. & KROLL, W. 1978. Practice effects on fractionated response time related to age and activity level. *Journal Of Motor Behavior,* 10**,** 275-286.

COHEN, R., MITCHELL, C., DOTAN, R., GABRIEL, D., KLENTROU, P. & FALK, B. 2010. Do neuromuscular adaptations occur in endurance-trained boys and men? *Applied Physiology, Nutrition & Metabolism,* 35**,** 471-479.

COOMBS, R. & GARBUTT, G. 2002. Developments in the use of the hamstring/quadriceps ratio for the assessment of muscle balance. *Journal of Sports Science & Medicine,* 1**,** 56-62.

COOPER, R., MORRIS, H. & ARENDT, L. 2011. *Acute Knee Injuries,* Australia, McGraw Hill.

DALLEAU, G., BELLI, A., VIALE, F., LACOUR, J. R. & BOURDIN, M. 2004. A Simple Method for Field Measurements of Leg Stiffness in Hopping. *International Journal of Sports Medicine,* 25**,** 170-176.

DARGEL, J., GOTTER, M., MADER, K., PENNIG, D., KOEBKE, J. & SCHMIDT-WIETHOFF, R. 2007. Biomechanics of the anterior cruciate ligament and implications for surgical reconstruction. *Strategies In Trauma And Limb Reconstruction (Online),* 2**,** 1-12.

DAVENPORT, G. 2011. The effect of a simulated football match on functional dynamic stability of the knee in male youth professional players. Unpublished Masters Thesis (UK).

DE STE CROIX, M., DEIGHAN, M. & ARMSTRONG, N. 2007. Functional Eccentric-Concentric Ratio of Knee Extensors and Flexors in Pre-Pubertal Children, Teenagers and Adult Males and Females. *International Journal of Sports Medicine,* 28**,** 768-772.

DE STE CROIX, M. & DEIGHAN, M. A. 2012. Dynamic Knee Stability During Childhood. *In:* DE STE CROIX, M. & KORFF, T. (eds.) *Paediatric biomechanics and motor control : theory and application.* London; New York: Routledge.

DE STE CROIX, M., DEIGHAN, M. A. & ARMSTRONG, N. 2003. Assessment and interpretation of isokinetic muscle strength during growth and maturation. *Sports Medicine,* 33**,** 727-743.

DE STE CROIX, M. B. A., DEIGHAN, M. A., RATEL, S. & ARMSTRONG, N. 2009. Age- and sex-associated differences in isokinetic knee muscle endurance between young children and adults. *Applied Physiology, Nutrition & Metabolism,* 34**,** 725-731.

DEHAVEN, K. E. & LINTNER, D. M. 1986. Athletic injuries: comparison by age, sport, and gender. / Traumatismes sportifs: comparaison selon l' age, le sport et le sexe. *American Journal of Sports Medicine,* 14**,** 218-224.

DEIGHAN, M. A., SERPELL, B. G., BITCOM, M. J. & DE STE CROIX, M. 2012. Knee joint strength ratios and effects of hip position in Rugby players. *Journal of Strength and Conditioning Research,* 26**,** 1959-1966.

DELEXTRAT, A., BAKER, J., COHEN, D. & CLARKE, N. 2011. Effect of a simulated soccer match on the functional hamstrings-to-quadriceps ratio in amateur female players. *Scandinavian Journal of Medicine & Science in Sports*.

DEMORAT, G., WEINHOLD, P., BLACKBURN, T., CHUDIK, S. & GARRETT, W. 2004. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine,* 32**,** 477-483.

DICK, R., FERRARA, M. S., AGEL, J., COURSON, R., MARSHALL, S. W., HANLEY, M. J. & REIFSTECK, F. 2007a. Descriptive Epidemiology of Collegiate Men's Football Injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 Through 2003-2004. *Journal of Athletic Training,* 42**,** 221-233.

DICK, R., PUTUKIAN, M., AGEL, J., EVANS, T. A. & MARSHALL, S. W. 2007b. Descriptive Epidemiology of Collegiate Women's Soccer Injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 Through 2002-2003. *Journal of Athletic Training,* 42**,** 278-285.

DUGAN, S. A. 2005. Sports-Related Knee Injuries in Female Athletes: What Gives? *American Journal of Physical Medicine & Rehabilitation,* 84**,** 122-130.

DUTTO, D. J. & SMITH, G. A. 2002. Changes in spring-mass characteristics during treadmill running to exhaustion. / Changements des caracteristiques de raideur des jambes lors d ' une course d ' effort sur tapis roulant. *Medicine & Science in Sports & Exercise,* 34**,** 1324-1331.

DVORAK, J. & JUNGE, A. 2000. Football injuries and physical symptoms: a review of the literature. / Blessures et autres symptomes physiques en football: revue de la litterature. *American Journal of Sports Medicine,* 28**,** S3-s9.

EKSTRAND, J., HÄGGLUND, M. & WALDÉN, M. 2011. Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine,* 45**,** 553-558.

ELNAGAR, Y. O. 2012. The effect of fatigue on sex differences in muscular and neuromuscular performance. Unpublished PhD thesis (UK).

EMERY, C. A. & MEEUWISSE, W. H. 2010. The effectiveness of a neuromuscular prevention strategy to reduce injuries in youth soccer: a cluster-randomised controlled trial. *British Journal Of Sports Medicine,* 44**,** 555-562.

ENGSTROM, B., JOHANSSON, C. & TORNKVIST, H. 1991. Soccer injuries among elite female players. *American Journal of Sports Medicine,* 19, 372-5.
FALK, B., USSELMAN, C., DOTAN, R., BRUNTON, L., KLENTROU, P., SHAW, J. & GABRIEL, D. 2009. Child-adult differences in muscle strength and activation pattern during isometric elbow flexion and extension. *Applied Physiology, Nutrition & Metabolism,* 34, 609-615.
FARLEY, C. T., BLICKHAN, R., SAITO, J. & TAYLOR, C. R. 1991. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *Journal Of Applied Physiology,* 71, 2127-2132.
FAUDE, O., JUNGE, A., KINDERMANN, W. & DVORAK, J. 2005. Injuries in Female Soccer Players A Prospective Study in the German National League. *American Journal of Sports Medicine,* 33, 1694-1700.
FAUNO, P. & WULFF JAKOBSEN, B. 2006. Mechanism of Anterior Cruciate Ligament Injuries in Soccer. *International Journal of Sports Medicine,* 27, 75-79.
FERRETTI, A., PAPANDREA, P., CONTEDUCA, F. & MARIANI, P. P. 1992. Knee ligament injuries in volleyball players. *American Journal of Sports Medicine,* 20, 203-207.
FIFA. 2006. *World football big count* [Online]. Available: http://www.fifa.com/mm/document/fifafacts/bcoffsurv/bigcount.statspackage_7024.pdf [Accessed 14/03/2012 2012].
FORBES, H., BUIIERS, A., LOVEII, A., MCNAUGHTO, R., POLMAN, R. C. & SIEGLER, J. C. 2009. Relative Torque Profiles of Elite Male Youth Footballers: Effects of Age and Pubertal Development. *International Journal of Sports Medicine,* 30, 592-597.
FORD, K. R., MYER, G. D., SCHMITT, L. C., UHL, T. L. & HEWETT, T. E. 2011. Preferential Quadriceps Activation in Female Athletes With Incremental Increases in Landing Intensity. *Journal of Applied Biomechanics,* 27, 215-222.
GALLAGHER, S. S., FINISON, K., GUYER, B. & GOODENOUGH, S. 1984. The incidence of injuries among 87,000 Massachusetts children and adolescents: results of the 1980-81 Statewide Childhood Injury Prevention Program Surveillance System. *The American Journal of Public Health,* 74, 1340-1347.
GAUL, C. A. 1996. Muscular strength and endurance. *In Measurement in pediatric exercise science, Human Kinetics Publishers, p.225-258.* United States.
GERODIMOS, V., MANDOU, V., ZAFEIRIDIS, A., IOAKIMIDIS, P., STAVROPOULOS, N. & KELLIS, S. 2003. Isokinetic peak torque and hamstring/quadriceps ratios in young basketball players: effects of age, velocity, and contraction mode. *Journal of Sports Medicine & Physical Fitness,* 43, 444-452.
GHORI, G., DONNE, B. & LUCKWILL, R. 1995. Relationship between torque and EMG activity of a knee extensor muscle during isokinetic concentric and eccentric actions. *Journal of Electromyography and Kinesiology,* 5, 109-115.
GIRARD, O., RACINAIS, S., KELLY, L., MILLET, G. & BROCHERIE, F. 2011. Repeated sprinting on natural grass impairs vertical stiffness but does not alter plantar loading in soccer players. *European Journal of Applied Physiology,* 111, 2547-2555.
GLEESON, N. P. 2001. Assessment of neuromuscular performance using electromyography. *In:* ESTON, R. G. & REILLY, T. (eds.) *Kinanthropometry and Exercise Physiology Laboratory Manual: Exercise physiology.* London: Routledge.

GRABINER, M. D. 1986. Bioelectric characteristics of the electromechanical delay preceding concentric contraction. / Caracteristiques bioelectriques du temps de latence electromecanique precedant une contraction concentrique. *Medicine & Science in Sports & Exercise,* 18**,** 37-43.
GRANATA, K. P., PADUA, D. A. & WILSON, S. E. 2002. Gender differences in active musculoskeletal stiffness. Part II: quantification of leg stiffness during functional hopping tasks. *Journal of Electromyography & Kinesiology,* 12**,** 127-135.
GREIG, M. 2008. The Influence of Soccer-Specific Fatigue on Peak Isokinetic Torque Production of the Knee Flexors and Extensors. *American Journal of Sports Medicine,* 36**,** 1403-1409.
GREIG, M. & SIEGLER, J. C. 2009. Soccer-Specific Fatigue and Eccentric Hamstrings Muscle Strength. *Journal of Athletic Training,* 44**,** 180-184.
GRIFFIN, J. W., TOOMS, R. E., VANDER ZWAAG, R., BERTORINI, T. E. & O'TOOLE, M. L. 1993. Eccentric muscle performance of elbow and knee muscle groups in untrained men and women. / Performance des muscles excentriques du coude et du genou chez l ' homme et la femme sedentaires. *Medicine & Science in Sports & Exercise,* 25**,** 936-944.
GRIFFIN, L. Y., ALBOHM, M. J., ARENDT, E. A., BAHR, R., BEYNNON, B. D., DEMAIO, M., DICK, R. W., ENGEBRETSEN, L., GARRETT JR, W. E., HANNAFIN, J. A., HEWETT, T. E., HUSTON, L. J., IRELAND, M. L., JOHNSON, R. J., LEPHART, S., MANDELBAUM, B. R., MANN, B. J., MARKS, P. H., MARSHALL, S. W., MYKLEBUST, G., NOYES, F. R., POWERS, C., SHIELDS JR, C., SHULTZ, S. J., SILVERS, H., SLAUTERBECK, J., TAYLOR, D. C., TEITZ, C. C., WOJTYS, E. M. & YU, B. 2006. Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries A Review of the Hunt Valley II Meeting, January 2005. *American Journal of Sports Medicine,* 34**,** 1513-1532.
GRIMSHAW, P. 2006. *Sport and exercise biomechanics*, BIOS Scientific Publ.
GRIMSHAW, P., LEES, A., FOWLER, N. & BURDEN, A. 2007. *Sport and exercise biomechanics* [Online]. New York: Taylor & Francis Group. Available: http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=190489.
GROSSET, J.-F., LAPOLE, T., MORA, I., VERHAEGHE, M., DOUTRELLOT, P.-L. & PÉROT, C. 2010. Follow-up of ankle stiffness and electromechanical delay in immobilized children: Three cases studies. *Journal of Electromyography & Kinesiology,* 20**,** 642-647.
GROSSET, J.-F., MORA, I., LAMBERTZ, D. & PÉROT, C. 2007. Changes in stretch reflexes and muscle stiffness with age in prepubescent children. *Journal of Applied Physiology,* 102**,** 2352-2360.
HALIN, R., GERMAIN, P., BERCIER, S., KAPITANIAK, B. & BUTTELLI, O. 2003. Neuromuscular response of young boys versus men during sustained maximal contraction. / Etude des reponses neuromusculaires a des contractions maximales chez des garcons compares a des hommes. *Medicine & Science in Sports & Exercise,* 35**,** 1042-1048.
HALL, S. 2007. *Basic biomechanics* . Boston , Mass: Mcgraw-Hill.
HASS, C. J., SCHICK, E. A., TILLMAN, M. D., CHOW, J. W., BRUNT, D. & CAURAUGH, J. H. 2005. Knee Biomechanics during Landings: Comparison of Pre- and Postpubescent Females. *Medicine & Science in Sports & Exercise,* 37**,** 100-107.

HAWKINS, R. D., HULSE, M. A., WILKINSON, C., HODSON, A. & GIBSON, M. 2001. The association football medical research programme: an audit of injuries in professional football. / Programme de recherche medicale sur le football en Angleterre: enquete sur les blessures dans le football professionnel. *British Journal of Sports Medicine,* 35**,** 43-47.

HERMENS, H. J., FRERIKS, B., DISSELHORST-KLUG, C. & RAU, G. 2000. Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology,* 10**,** 361-374.

HERTEL, J., DORFMAN, J. H. & BRAHAM, R. A. 2004. Lower extremity malalignments and anterior cruciate ligament injury history. *Journal of Sports Science Medicine,* 3**,** 220-225.

HEWETT, T. E. 2000. Neuromuscular and hormonal factors associated with knee injuries in female athletes: strategies for intervention. / Facteurs neuromusculaires et hormonaux associes aux blessures du genou chez les athletes feminines: strategies d'intervention. *Sports Medicine,* 29**,** 313-327.

HEWETT, T. E., FORD, K. R., HOOGENBOOM, B. J. & MYER, G. D. 2010. Understanding And Preventing ACL Injuries: Current Biomechanical And Epidemiologic Considerations- Update 2010. *North American Journal of Sports Physical Therapy,* 5**,** 234-251.

HEWETT, T. E., MYER, G. D., FORD, K. R. & SLAUTERBECK, J. R. 2007a. Dynamic neuromuscular analysis training for preventing anterior cruciate ligament injury in female athletes. *Instructional Course Lectures,* 56**,** 397-406.

HEWETT, T. E., SHULTZ, S. J., MEDICINE, A. O. S. F. S. & GRIFFIN, L. Y. 2007b. *Understanding and preventing noncontact ACL injuries*, Human Kinetics.

HEWETT, T. E., ZAZULAK, B. T., MYER, G. D. & FORD, K. R. 2005. A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *British Journal of Sports Medicine,* 39**,** 347-350.

HICKS, A. L., KENT-BRAUN, J. & DITOR, D. S. 2001. Sex differences in human skeletal muscle fatigue. *Exercise and sport sciences reviews,* 29**,** 109.

HILDEBRAND, K. A., MOHTADI, N. G. H., KIEFER, G. N., TEDFORD, K., MASSEY, A. & BRANT, R. 1994. Thigh muscle strength in preadolescent girls. *Clinical Journal of Sport Medicine,* 4**,** 108-112.

HOBARA, H., KIMURA, K., OMURO, K., GOMI, K., MURAOKA, T., ISO, S. & KANOSUE, K. 2008. Determinants of difference in leg stiffness between endurance- and power-trained athletes. *Journal of Biomechanics,* 41**,** 506-514.

HOBARA, H., MURAOKA, T., OMURO, K., GOMI, K., SAKAMOTO, M., INOUE, K. & KANOSUE, K. 2009. Knee stiffness is a major determinant of leg stiffness during maximal hopping. *Journal of Biomechanics,* 42**,** 1768-1771.

HOLCOMB, W. R., RUBLEY, M. D., LEE, H. J. & GUADAGNOLI, M. A. 2007. Effect of Hamstring-Emphasized Resistance Training On Hamstring:Quadriceps Strength Ratios. *Journal of Strength & Conditioning Research,* 21**,** 41-47.

HOPKINS, W. G. 2000a. Measures of reliability in sports medicine and science. / Mesures de fiabilite en medecine du sport et science du sport. *Sports Medicine,* 30**,** 1-15.

HOPKINS, W. G. 2000b. *Reliability from consecutive pairs oftrials (Excel spreadsheet).* [Online]. Available: http://www.sportsci.org/resource/stats/index.html. [Accessed 13/6/2012].

HORITA, T. & ISHIKO, T. 1987. Relationships between muscle lactate accumulation and surface EMG activities during isokinetic contractions in man. *European Journal of Applied Physiology & Occupational Physiology,* 56**,** 18-23.

HOWATSON, G. 2010. The impact of damaging exercise on electromechanical delay in biceps brachii. *Journal of Electromyography & Kinesiology,* 20**,** 477-481.
HUGHES, G. & WATKINS, J. 2006. A Risk-Factor Model for Anterior Cruciate Ligament Injury. *Sports Medicine,* 36**,** 411-428.
HUNTER, I. & SMITH, G. 2007. Preferred and optimal stride frequency, stiffness and economy: changes with fatigue during a 1-h high-intensity run. *European Journal of Applied Physiology,* 100**,** 653-661.
HÄGGLUND, M., WALDÉN, M. & EKSTRAND, J. 2009. Injuries among male and female elite football players. *Scandinavian Journal of Medicine & Science in Sports,* 19**,** 819-827.
IGA, J., GEORGE, K., LEES, A. & REILLY, T. 2009. Cross-sectional investigation of indices of isokinetic leg strength in youth soccer players and untrained individuals. *Scandinavian Journal of Medicine & Science in Sports,* 19**,** 714-719.
JACOBSON, I. & TEGNER, Y. 2007. Injuries among Swedish female elite football players: a prospective population study. *Scandinavian Journal of Medicine & Science in Sports,* 17**,** 84-91.
KAWAKAMI, Y., KANEHISA, H., IKEGAWA, S. & FUKUNAGA, T. 1993. Concentric and eccentric muscle strength before, during and after fatigue in 13 year-old boys. *European Journal of Applied Physiology & Occupational Physiology,* 67**,** 121-124.
KELLIS, E. & KATIS, A. 2007. Quantification of Functional Knee Flexor to Extensor Moment Ratio Using Isokinetics and Electromyography. *Journal of Athletic Training,* 42**,** 477-485.
KELLIS, S., GERODIMOS, V., KELLIS, E. & MANOU, V. 2001. Bilateral isokinetic concentric and eccentric strength profiles of the knee extensors and flexors in young soccer players. *Isokinetics & Exercise Science,* 9**,** 31-39.
KENNEY, W. L., WILMORE, J. & COSTILL, D. 2011. Children and Adolescents in Sport and Exercise. *In:* KENNEY, W. L., WILMORE, J. & COSTILL, D. (eds.) *Physiology of Sport and Exercise.* 5th ed. Champaign IL, USA: Human Kinetics.
KENT BRAUN, J. A. 1999. Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort (Contribution centrale et peripherique a la fatigue musculaire chez l'homme pendant un effort soutenu). *European Journal of Applied Physiology,* 80**,** 57-63.
KIM, D. & HONG, J. 2011. Hamstring to quadriceps strength ratio and noncontact leg injuries: A prospective study during one season. *Isokinetics & Exercise Science,* 19**,** 1-6.
KONRAD, P. 2005. ABC of EMGA practical introduction to kinesiological electromyography.
KORFF, T., HORNE, S. L., CULLEN, S. J. & BLAZEVICH, A. J. 2009. Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence. *The Journal Of Experimental Biology,* 212**,** 3737-3742.
KROSSHOUG, T., ANDERSEN, T. E., OLSEN, O. E. O., MYKLEBUST, G. & BAHR, R. 2005. Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. *British Journal of Sports Medicine,* 39**,** 330-339.
KUBO, K., MORIMOTO, M., KOMURO, T., TSUNODA, N., KANEHISA, H. & FUKUNAGA, T. 2007. Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint. *European Journal Of Applied Physiology,* 99**,** 235-243.

KUITUNEN, S., AVELA, J., KYROLAINEN, H., NICOL, C. & KOMI, P. 2002. Acute and prolonged reduction in joint stiffness in humans after exhausting stretch-shortening cycle exercise. / Reduction prolongee de la raideur des articulations chez des humains suite a une courte serie d ' exercices d ' etirement. *European Journal Of Applied Physiology,* **88**, 107-116.
LAFFAYE, G., BARDY, B. G. & DUREY, A. 2005. Leg stiffness and expertise in men jumping. *Medicine & Science in Sports & Exercise,* **37**, 536-543.
LAMBERTZ, D., MORA, I., GROSSET, J. F. & PEROT, C. 2003. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *Journal of Applied Physiology,* **95**, 64-72.
LAZARIDIS, S., BASSA, E., PATIKAS, D., GIAKAS, G., GOLLHOFER, A. & KOTZAMANIDIS, C. 2010. Neuromuscular differences between prepubescents boys and adult men during drop jump. *European Journal Of Applied Physiology,* **110**, 67-74.
LEBIEDOWSKA, M. K. & FISK, J. R. 1999. Passive dynamics of the knee joint in healthy children and children affected by spastic paresis. *Clinical Biomechanics (Bristol, Avon),* **14**, 653-660.
LEES, A., VANRENTERGHEM, J. & CLERCQ, D. D. 2004. Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics,* **37**, 1929-1940.
LEPHART, S. M., FERRIS, C. M., RIEMANN, B. L., MYERS, J. B. & FU, F. H. 2002. Gender differences in strength and lower extremity kinematics during landing. *Clinical Orthopaedics & Related Research,* **401**, 162-169.
LINDENFELD, T. N., SCHMITT, D. J., HENDY, M. P., MANGINE, R. E. & NOYES, F. R. 1994. Incidence of injury in indoor soccer. *American Journal of Sports Medicine,* **22**, 364-371.
LISLEVAND, M., STEFFEN, K., JUNGE, A., DVORAK, J. & ANDERSEN, T. E. 2011. Injury surveillance during a national female youth football tournament in kenya. *British Journal of Sports Medicine,* **45**, 360-360.
LLOYD, R. S., OLIVER, J. L., HUGHES, M. G. & WILLIAMS, C. A. 2009. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *Journal of Sports Sciences,* **27**, 1565-1573.
LLOYD, R. S., OLIVER, J. L., HUGHES, M. G. & WILLIAMS, C. A. 2012. Age-related differences in the neural regulation of stretch–shortening cycle activities in male youths during maximal and sub-maximal hopping. *Journal of Electromyography & Kinesiology,* **22**, 37-43.
LLOYD, R. S., OLIVER, J. L., HUGHES, M. G. & WILLIAMS, P. C. A. 2011. The effects of 4-weeks plyometric training on reactive strength index and leg stiffness in male youths. *The Journal of Strength & Conditioning Research*.
LOVELL, R., KNAPPER, B. & SMALL, K. 2008. Physiological responses to SAFT90: a new soccer-specific match simulation. *Coaching and Sports Science*.
MANDELBAUM, B. R., SILVERS, H. J., WATANABE, D. S., KNARR, J. F., THOMAS, S. D., GRIFFIN, L. Y., KIRKENDALL, D. T. & GARRETT, W., JR. 2005. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *American Journal of Sports Medicine,* **33**, 1003-1010.
MCMAHON, T. A. & CHENG, G. C. 1990. Mechanics of running. How does stiffness couple with speed? *Journal of Biomechanics,* **23**, 65-78.
MCNAIR, P. J., MARSHALL, R. N. & MATHESON, J. A. 1990. Important features associated with acute anterior cruciate ligament injury. *The New Zealand Medical Journal,* **103**, 537-539.

MINSHULL, C. 2004. Exercise, neuromuscular performance and stability of synovial joints. Unpublished PhD thesis (UK).
MIRWALD, R. L., BAXTER-JONES, A. D. G., BAILEY, D. A. & BEUNEN, G. P. 2002. An assessment of maturity from anthropometric measurements. / Evaluation de la maturite a partir de mesures anthropometriques. *Medicine & Science in Sports & Exercise,* 34**,** 689-694.
MOHR, M., KRUSTRUP, P. & BANGSBO, J. 2005. Fatigue in soccer: A brief review. *Journal of Sports Sciences,* 23**,** 593-599.
MOHTADI, N. G. H., KIEFER, G. N., TEDFORD, K. & WATTERS, S. 1990. Concentric and eccentric quadriceps torque in pre-adolescent males. *Canadian Journal of Sport Sciences,* 15**,** 240-243.
MORIN, J.-B., SAMOZINO, P. & MILLET, G. Y. 2011. Changes in Running Kinematics, Kinetics, and Spring-Mass Behavior over a 24-h Run. *Medicine & Science in Sports & Exercise,* 43**,** 829-836.
MURPHY, D. F., CONNOLLY, D. A. J. & BEYNNON, B. D. 2003. Risk factors for lower extremity injury: a review of the literature. *British Journal of Sports Medicine,* 37**,** 13-29.
MYER, G. D., BRENT, J. L., FORD, K. R. & HEWETT, I. E. 2008. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. *British Journal of Sports Medicine,* 42**,** 614-619.
MYER, G. D., FORD, K. R. & HEWETT, T. E. 2004. Rationale and Clinical Techniques for Anterior Cruciate Ligament Injury Prevention Among Female Athletes. *Journal of Athletic Training,* 39**,** 352-352.
MYER, G. D., FORD, K. R., KHOURY, J., SUCCOP, P. & HEWETT, T. E. 2011. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *British Journal of Sports Medicine,* 45**,** 245-252.
MYKLEBUST, G. & BAHR, R. 2005. Return to play guidelines after anterior cruciate ligament surgery *British Journal of Sports Medicine,* 39**,** 127-131.
NICHOLAS, C. W., NUTTALL, F. E. & WILLIAMS, C. 2000. The Loughborough Intermittent Shuttle Test: a field test that simulates the activity pattern of soccer. *Journal of Sports Sciences,* 18**,** 97-104.
NICOL, C. & AVELA, J. 2006. The Stretch-Shortening Cycle: A Model to Study Naturally Occurring Neuromuscular Fatigue. *Sports Medicine,* 36**,** 977-999.
NILSSON, J., TESCH, P. & THORSTENSSON, A. 1977. Fatigue and EMG of repeated fast voluntary contractions in man. *Acta Physiologica Scandinavica,* 101**,** 194-198.
OLIVEIRA, A. D. S. C., CAPUTO, F., GONÇALVES, M. & DENADAI, B. S. 2009. Heavy-intensity aerobic exercise affects the isokinetic torque and functional but not conventional hamstrings:quadriceps ratios. *Journal of Electromyography & Kinesiology,* 19**,** 1079-1084.
OLIVER, J. 2008. Sprint performance and neuromuscular functioning in male youth footballers. Unpublished PhD Thesis (UK).
OLIVER, J. L. & SMITH, P. M. 2010. Neural control of leg stiffness during hopping in boys and men. *Journal of Electromyography & Kinesiology,* 20**,** 973-979.
OLSEN, O.-E., MYKLEGUST, G., ENGEBRETSEN, L. & BAHR, R. 2004. Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball: A Systematic Video Analysis. *American Journal of Sports Medicine,* 32**,** 1002-1012.

OLSEN, O. E., MYKLEBUST, G., ENGEBRETSEN, L., HOLME, I. & BAHR, R. 2003. Relationship between floor type and risk of ACL injury in team handball. *Scandinavian Journal of Medicine & Science in Sports,* 13**,** 299-304.
OSTENBERG, A. & ROOS, H. 2000. Injury risk factors in female European football. A prospective study of 123 players during one season. *Scandinavian Journal of Medicine & Science in Sports,* 10**,** 279-285.
OSTERNIG, L. R. (ed.) 2000. *Assessing Human Performance,* Champaign, Ill. [u.a.]: Human Kinetics Publ.
PADUA, D. A., ARNOLD, B. L., CARCLA, C. R. & GRANATA, K. P. 2005. Gender Differences in Leg Stiffness and Stiffness Recruitment Strategy During Two-Legged Hopping. *Journal of Motor Behavior,* 37**,** 111-125.
PADUA, D. A., ARNOLD, B. L., PERRIN, D. H., GANSNEDERS, B. M., CARCIA, C. R. & GRANATA, K. P. 2006. Fatigue, Vertical Leg Stiffness, and Stiffness Control Strategies in Males and Females. *Journal of Athletic Training,* 41**,** 294-304.
PALASTANGA, N., FIELD, D. & SOAMES, R. 2006. *Anatomy and human movement*, Butterworth-Heinemann.
PALASTANGA, N. & SOAMES, R. 2012. *Anatomy and human movement structure and function,* Edinburgh; New York, Churchill Livingstone.
QUATMAN, C. E., QUATMAN-YATES, C. C. & HEWETT, T. E. 2010. A 'Plane' Explanation of Anterior Cruciate Ligament Injury Mechanisms. *Sports Medicine,* 40**,** 729-746.
RAHNAMA, N., LEES, A. & REILLY, T. 2006. Electromyography of selected lower-limb muscles fatigued by exercise at the intensity of soccer match-play. *Journal of Electromyography & Kinesiology,* 16**,** 257-263.
RAHNAMA, N., REILLY, T. & LEES, A. 2002. Injury risk associated with playing actions during competitive soccer. *British Journal of Sports Medicine,* 36**,** 354-359.
RAHNAMA, N., REILLY, T., LEES, A. & GRAHAM-SMITH, P. 2003. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *Journal of Sports Sciences,* 21**,** 933-942.
RATEL, S., DUCHÉ, P. & WILLIAM, C. A. 2006. Muscle Fatigue during High-Intensity Exercise in Children. *Sports Medicine,* 36**,** 1031-1065.
RENSTROM, P., LJUNGQVIST, A., ARENDT, E., BEYNNON, B., FUKUBAYASHI, T., GARRETT, W., GEORGOULIS, T., HEWETT, T. E., JOHNSON, R., KROSSHAUG, T., MANDELBAUM, B., MICHELI, L., MYKLEBUST, G., ROOS, E., ROOS, H., SCHAMASCH, P., SHULTZ, S., WERNER, S., WOJTYS, E. & ENGEBRETSEN, L. 2008. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *British Journal of Sports Medicine,* 42**,** 394-412.
ROIG, M., O'BRIEN, K., KIRK, G., MURRAY, R., MCKINNON, P., SHADGAN, B. & REID, W. D. 2009. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *British Journal of Sports Medicine,* 43**,** 556-568.
ROOS, H., ORNELL, M., GARDSELL, P., LOHMANDER, L. S. & LINDSTRAND, A. 1995. Soccer after anterior cruciate ligament injury -- an incompatible combination? A national survey of incidence and risk factors and a 7-year follow-up of 310 players. *Acta Orthopaedica Scandinavica,* 66**,** 107-112.
ROSENBLOOM, C. A., LOUCKS, A. B. & EKBLOM, B. 2006. Special populations: The female player and the youth player. *Journal of Sports Sciences,* 24**,** 783-793.
ROWLAND, T. W. 2005. The Metabolic Machinery. *In:* ROWLAND, T. W. (ed.) *Children's Exercise Physiology.* Champaign, IL; USA: Human Kinetics.

RUMPF, M. C. & CRONIN, J. 2012. Injury Incidence, Body Site, and Severity in Soccer Players Aged 6-18 Years: Implications for Injury Prevention. *Strength & Conditioning Journal,* 34**,** 20-31.

RUSSELL, P. J., CROCE, R. V., SWARTZ, E. E. & DECOSTER, L. C. 2007. Knee-Muscle Activation during Landings: Developmental and Gender Comparisons. *Medicine & Science in Sports & Exercise,* 39**,** 159-169.

SCHIFF, M. A., MACK, C. D., POLISSAR, N. L., LEVY, M. R., DOW, S. P. & O'KANE, J. W. 2010. Soccer Injuries in Female Youth Players: Comparison of Injury Surveillance by Certified Athletic Trainers and Internet. *Journal of Athletic Training,* 45**,** 238-242.

SHEA, K. G., PFEIFFER, R., WANG, J. H., CURTIN, M. & APEL, P. J. 2004. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *Journal Of Pediatric Orthopedics,* 24**,** 623-628.

SHIMOKOCHI, Y. & SHULTZ, S. J. 2008. Mechanisms of Noncontact Anterior Cruciate Ligament Injury. *Journal of Athletic Training,* 43**,** 396-408.

SHULTZ, S. J. 2008. ACL Injury in the Female Athlete: A Multifactorial Problem That Remains Poorly Understood. *Journal of Athletic Training,* 43**,** 455-455.

SHULTZ, S. J. & PERRIN, D. H. 1999. Using surface electromyography to assess sex differences in neuromuscular response characteristics. *Journal of Athletic Training,* 34**,** 165-176.

SILVERS, H. J. & MANDELBAUM, B. R. 2007. Prevention of anterior cruciate ligament injury in the female athlete. *British Journal of Sports Medicine,* 41**,** i52-i59.

SMALL, K., MCNAUGHTON, L., GREIG, M. & LOVELL, R. 2010. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *Journal of Science & Medicine in Sport,* 13**,** 120-125.

SMALL, K. A. 2008. *Effect of Fatigue on Hamstring Strain Injury Risk in Soccer.* Doctor of Philosophy, University of Hull.

SMITH, M. P., SIZER, P. S. & JAMES, C. R. 2009. Effects of fatigue on frontal plane knee motion, muscle activity, and ground reaction forces in men and women during landing. *Journal of Sports Science & Medicine,* 8**,** 419-427.

STOLEN, T., CHAMARI, K., CASTAGNA, C. & WISLOFF, U. 2005. Physiology of Soccer: An Update. *Sports Medicine,* 35**,** 501-536.

THE FA. 2011. *Women's and Girls Football* [Online]. Available: http://www.thefa.com/GetIntoFootball/Players/PlayersPages/WomensAndGirls [Accessed 31/07/2012].

VESCOVI, J. D. & VANHEEST, J. L. 2010. Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. *Scandinavian Journal of Medicine & Science in Sports,* 20**,** 394-402.

VOS, E. J., HARLAAR, J. & VAN INGEN SCHENAU, G. J. 1991. Electromechanical delay during knee extensor contractions. / Reponse electromecanique lors de contractions des muscles extenseurs du genou. *Medicine & Science in Sports & Exercise,* 23**,** 1187-1193.

WALDÉN, M., HÄGGLUND, M., WERNER, J. & EKSTRAND, J. 2011. The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. *Knee Surgery, Sports Traumatology, Arthroscopy,* 19**,** 3-10.

WEINER, J. S. & LOURIE, J. A. 1981. *Practical Human Biology,* London, Academic Press.

WILMORE, J. H., COSTILL, D. L. & KENNEY, W., L 2008. *Physiology of Sport And Exercise,* Champaign, IL, Human Kinetics.

WILSON, J. M. & FLANAGAN, E. P. 2008. The role of elastic energy in activities with high force and power requirements: a brief review. *Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins),* 22**,** 1705-1715.

WINTER, E. M. & BROOKES, F. B. C. 1991. Electromechanical response times and muscle elasticity in men and women. *European Journal of Applied Physiology & Occupational Physiology,* 63**,** 124-128.

WOJTYS, E. M., HUSTON, L. J., TAYLOR, P. D. & BASTIAN, S. D. 1996. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. / Adaptations neuromusculaires lors des programmes d'entrainement isocinetique, isotonique et d'agilite. *American Journal of Sports Medicine,* 24**,** 187-192.

WOO, S. L., HOLLIS, J. M., ADAMS, D. J., LYON, R. M. & TAKAI, S. 1991. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med,* 19**,** 217-25.

WORRELL, T. W., DENEGAR, C., ARMSTRONG, S. & PERRIN, D. 1990. Effect of body position on hamstring muscle group average torque. *Journal of Orthopedic Sports and Physical Therapy,* 11**,** 449-452.

WRIGHT, J., BALL, N. & WOOD, L. 2009. Fatigue, H/Q ratios and muscle coactivation in recreational football players. *Isokinetics & Exercise Science,* 17**,** 161-167.

YAVUZ, S. U., SENDEMIR-URKMEZ, A. & TÜRKER, K. S. 2010. Effect of gender, age, fatigue and contraction level on electromechanical delay. *Clinical Neurophysiology: Official Journal Of The International Federation Of Clinical Neurophysiology,* 121**,** 1700-1706.

YEUNG, S. S., SUEN, A. M. Y. & YEUNG, E. W. 2009. A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *British Journal of Sports Medicine,* 43**,** 589-594.

YU, B., KIRKENDALL, D. T. & GARRETT JR, W. E. 2002a. Anterior cruciate ligament injuries in female athletes: anatomy, physiology, and motor control. *Sports Medicine & Arthroscopy Review,* 10**,** 58-68.

YU, B., KIRKENDALL, D. T., TAFT, T. N. & GARRETT, W. E., JR. 2002b. Lower extremity motor control-related and other risk factors for noncontact anterior cruciate ligament injuries. *Instructional Course Lectures,* 51**,** 315-324.

ZHOU, S., LAWSON, D. L., MORRISON, W. E. & FAIRWEATHER, I. 1995. Electromechanical delay of knee extensors : the normal range and the effects of age and gender. *Journal of Human Movement Studies,* 28**,** 127-146.

ZHOU, S., MCKENNA, M. J., LAWSON, D. L., MORRISON, W. E. & FAIRWEATHER, I. 1996. Effects of fatigue and sprint training on electromechanical delay of knee extensor muscles. *European Journal of Applied Physiology & Occupational Physiology,* 72**,** 410-416.

CHAPTER IX
APPENDICIES

Appendix A

PARTICIPANT INFORMATION SHEET

Protect her knees - Exploring the role of football specific fatigue on dynamic knee stability in female youth football players

Dear Team member,

Thank you for your interest in taking part in this study. This sheet will tell you a bit more about the study and what we would like you to do. Please read this carefully. If you decide not to take part it will not change your relationship with the research team, the University or Club.

What is the project about?

We are interested in looking at the effect of football fatigue on the lower leg, particularly on the knee in female youth players. This is a unique study investigating how well the muscles work when they are fatigued, so that we can design training to try to reduce the risk of injury.

About the study

This study has been funded by UEFA and will be run by a research team from the University of Gloucestershire. All researchers have experience working with athletes/children and have completed a full CRB check. The study has also been approved by the University Research Ethics Sub-Committee (RESC).

Who is taking part in the study?

Females aged 12-17 years who are participating in professional women's football in the UK (players linked to Bristol Academy Ladies).

You will visit the University of Gloucestershire twice and we will come to one of your club training sessions to do some quick tests.

On your first visit to the University all tests will be explained to you and you will have a go on a machine called an isokinetic dynamometer to get used to the movements you will be performing, as well as practice the running test. Your posture and landing technique will also be examined using a camera system. Other things like height and weight will be measured on this visit to the University.

On your second visit to the University you will perform the actual tests. Initially, you will perform a standard ten-minute warm-up that is usually performed at your club before matches. This will include running and movements familiar to you. You will then perform a baseline test involving a repeated kicking action with your preferred leg on the isokinetic dynamometer. There will be 30-seconds rest between each effort. Measurements of muscular activity will be taken using pads placed on different muscles in the leg.

Following baseline testing players will undertake the SAFT^{90} exercise protocol. This protocol involves football specific movement around a sports hall for the same duration as your matches with a half-time interval, also the same as on a match day. 5-minutes after finishing, you will repeat the test on the isokinetic dynamometer a second time.

Water will be available to fill up drinks bottles when you visit the University in order to keep you hydrated throughout the testing session.

When we come to one of your club trainings, you will perform a variety of hopping and jumping tasks on a mobile contact mat. This will include jumping on both feet continuously for about 10 seconds. You will also complete a Functional Movement Screen (FMS) which examines how you move when you perform a squat, a hurdle step, a lunge, an assessment of shoulder mobility, a straight leg raise, a push up and a core stability exercise.

When will I do it?

Whenever you and the laboratory are available we will arrange a time for you to come to the laboratory. If you wish you may come as a group. All tests at the University of Gloucestershire will follow our RESC approved laboratory guidelines. Parents/guardians will be informed of the specific arrangements via written documentation.

Can I change my mind?

You can stop being a part of the study at any time, including anytime throughout data collection. All you have to do is let us know that you no longer want to take part. This will not affect your relationship with the research team, the University or Club.

What will you do with the information?

All the information collected will be stored on a computer using ID codes and the results will only be seen by the research team. Your name will never be used. The data will be stored on password protected computers and in lockable filing cabinets for 10 years and will then be destroyed.

The tests we perform are nothing to do with performance and your coaches will not use the results to pick the team. The results could be used to design a specific individual training program by your coaches in order to reduce the risk of future injury. If you want your coaches to have access to your individual results in order to make changes to your training, you should fill in the Data consent form.

What if I have any questions?

If you have any questions then please feel free to ask either of the people below at any time.

What do I do next?

If you have read and understood everything that we want you to do and are happy to take part please sign the consent form that is attached to this sheet.

Miss Abigail Priestley
MSc by Research Student
Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

Abigailpriestley@connect.glos.ac.uk

Dr Mark De Ste Croix
Lead Researcher/Project manager
Reader in Children's Physiology
School of Sport and Exercise
University of Gloucestershire

mdestecroix@glos.ac.uk

Project mobile phone number: 07531912896

APPENDIX B

PARTICIPANT CONSENT FORM

Protect her knees - Exploring the role of football specific fatigue on dynamic knee stability in female youth football players

Sport & Exercise Laboratories

Participant informed consent form

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw from the tests at any point. I confirm that I have completed a health questionnaire and I am in a fit condition to undertake the required exercise.

Participant

Name:……………………………………

Signed:…………………………………………… Date:…………………

Miss Abigail Priestley

MSc by Research Student
Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

Abigailpriestley@connect.glos.ac.uk

Dr Mark De Ste Croix

Lead Researcher/Project manager
Reader in Children's Physiology
School of Sport and Exercise
University of Gloucestershire

destecroix@glos.ac.uk

Project mobile phone number: 07531912896

APPENDIX C

DATA RELEASE FORM

Protect her knees - Exploring the role of football specific fatigue on dynamic knee stability in female youth football players

(Data Consent Form)

Dear Participant,

The data gathered in this study will not be passed on to any other party and will remain anonymous if you so wish. However, the data may be beneficial for you if passed on to the relevant members of your club.

The data collected does not relate to actual performance, therefore your coaches will not use the data for team selection. It is purely to highlight any specific areas that could be improved through an individual training program in order to reduce your risk to injury.

If you wish for your data to be made available for your team management please sign below.

Participant

Name:………………………………………..

Signed………………………………………..   Date:……………………………

Thank you again for your cooperation.

Miss Abigail Priestley

MSc by Research Student
Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

Abigailpriestley@connect.glos.ac.uk

Dr Mark De Ste Croix

Lead Researcher/Project manager
Reader in Children's Physiology
School of Sport and Exercise
University of Gloucestershire

mdestecroix@glos.ac.uk

Project mobile phone number: 07531912896

APPENDIX D

PARENT/GUARDIAN CONSENT FORM

Protect her knees - Exploring the role of football specific fatigue on dynamic knee stability in female youth football players

Sport & Exercise Laboratories

Parent/ guardian informed consent form

I have had full details of the tests my child is about to complete explained to me. I understand the risks and benefits involved, and that she is free to withdraw from the tests at any point. I confirm my child has completed a health questionnaire and is in a fit condition to undertake the required exercise.

Parent/ guardian

Name:……………………………………

Signed:…………………………………………….. Date:………………..

Miss Abigail Priestley

MSc by Research Student
Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire
Abigailpriestley@connect.glos.ac.uk

Dr Mark De Ste Croix

Lead Researcher/Project manager
Reader in Children's Physiology
School of Sport and Exercise
University of Gloucestershire
destecroix@glos.ac.uk

Project mobile phone number: 07531912896

APPENDIX E

RESEARCH ETHICS SUB-COMMITTEE APPROVAL

UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

Research Ethics Sub-Committee Approval

Protect her knees: Exploring the role of football specific fatigue on dynamic knee stability in female youth football players.

After attending the Research Ethics Sub-Committee meeting to discuss the project and making the suggested amendments, the project has again been considered and we are pleased to inform you that it has now been approved.

Thank you for taking the time to attend the RESC meeting and good luck with your project.

Best wishes

Dr Malcolm MacLean
Chair - Research Ethics Sub-Committee

Associate Dean, Academic Frameworks
University of Gloucestershire
The Park
Cheltenham GL50 2RH

APPENDIX F
HEALTH QUESTIONAIRE

SPORT & EXERCISE LABORATORIES

Health Questionnaire

About this questionnaire:

The purpose of this questionnaire is to gather information about your health and lifestyle. We will use this information to decide whether you are eligible to take part in the testing for which you have volunteered. It is important that you answer the questions truthfully. The information you give will be treated in confidence. Your completed form will be stored securely for 5 years and then destroyed.

Section 1, which has been completed by the tester, provides basic information about the testing for which you have volunteered. Sections 2 to 7 are for you to complete: please circle the appropriate response or write your answer in the space provided. Please also complete section 8. Sections 9 and 10 will be completed by the tester, after you have completed sections 2 to 8.

Section 1: The testing (completed by tester)

To complete the testing for which you have volunteered you will be required to undertake:

Moderate exercise (i.e. exercise that makes you breathe more heavily than you do at rest but not so heavily that you are unable to maintain a conversation) ☐

Vigorous exercise (i.e. exercise that makes you breath so heavily that you are unable to maintain a conversation). ☐

The testing involves:

Walking	☐	Generating or absorbing high forces through your arms	☐
Running	☐	Generating/absorbing high forces through your shoulders	☐
Cycling	☐	Generating/absorbing high forces through your trunk	☐
Rowing	☐	Generating/ absorbing high forces through your hips	☐
Swimming	☐	Generating/ absorbing high forces through your legs	☐
Jumping	☐		

Section 2: General information

Name: ....…...…....………….. Sex: M F Age:

Height (approx.): ....………..……….. Weight (approx.):

Section 3: Initial considerations

1. Do any of the following apply to you? No Yes

   a) I have HIV, Hepatitis A, Hepatitis B or Hepatitis C
   b) I am pregnant
   c) I have a muscle or joint problem that could be aggravated by the testing described in section 1
   d) I am feeling unwell today
   e) I have had a fever in the last 7 days

   (If you have answered "Yes" to question 1, go straight to section 8)

Section 4: Habitual physical activity

2a. Do you typically perform moderate exercise (as defined in section 1) for 20 minutes or longer at least twice a week? No Yes

2b. Have you performed this type of exercise within the last 10 days? No Yes

3a. Do you typically perform vigorous exercise (as defined in section 1) at least once a week? No Yes

3b. Have you performed this type of exercise within the last 10 days? No Yes

Section 5: Known medical conditions

4. Do **any** of the following apply to you? No Yes

   a) I have had insulin-dependent diabetes for more than 15 years
   b) I have insulin-dependent diabetes and am over 30 years old
   c) I have non-insulin-dependent diabetes and am over 35 years old

5. Have you ever had a stroke? No Yes

6. Has your doctor ever said you have heart trouble? No Yes

7. Do **both** of the following apply to you? No Yes

   a) I take asthma medication
   b) I have experienced shortness of breath or difficulty with breathing in the last 4 weeks?

8. Do you have any of the following: cancer, COPD, cystic fibrosis, other lung disease, liver disease, kidney disease, mental illness, osteoporosis, severe arthritis, a thyroid problem? No Yes

   (If you have answered "Yes" to any questions in section 5, go straight to section 8.)

Section 6: Signs and symptoms

9.	Do you often have pains in your heart, chest, or the surrounding areas?	No	Yes
10.	Do you experience shortness of breath, either at rest or with mild exertion?	No	Yes
11.	Do you often feel faint or have spells of severe dizziness?	No	Yes
12.	Have you, in the last 12 months, experienced difficulty with breathing when lying down or been awakened at night by shortness of breath?	No No	Yes Yes
13.	Do you experience swelling or a buildup of fluid in or around your ankles?	No	Yes
14.	Do you often get the feeling that your heart is racing or skipping beats, either at rest or during exercise?	No	Yes
15.	Do you regularly get pains in your calves and lower legs during exercise that are not due to soreness or stiffness?	No	Yes
16.	Has your doctor ever told you that you have a heart murmur?	No	Yes
17.	Do you experience unusual fatigue or shortness of breath during everyday activities?	No	Yes

(If you have answered "Yes" to any questions in section 6, go straight to section 8.)

Section 7: Risk factors

18.	Does **either** of the following apply to you? a) I smoke cigarettes on a daily basis b) I stopped smoking cigarettes on a daily basis less than 6 months ago	No	Yes
19.	Has your doctor ever told you that you have high blood pressure?	No	Yes
20.	Has your doctor ever told you that you have high cholesterol?	No	Yes
21.	Has your father or any of your brothers had a heart attack, heart surgery, or a stroke before the age of 55?	No	Yes
22.	Has your mother or any of your sisters had a heart attack, heart surgery, or a stroke before the age of 65?	No	Yes
23.	Do **any** of the following apply to you? a) I have had insulin-dependent diabetes for less than 15 years b) I have insulin-dependent diabetes and am 30 or younger c) I have non-insulin-dependent diabetes and am 35 or younger	No	Yes

Section 8: Signatures

Participant: ………………………………………………………….. Date: ....………………......

Guardian*: ....………………….…....... Date: ....……………........

(*Required only if the participant is under 18 years of age.)

Section 9: Additional risk factors (to be completed by the tester if relevant)

24. Is the participant's body mass index >30 kg/m^2? No Yes

25. Has the participant answered no to questions 2a **and** 3a? No Yes

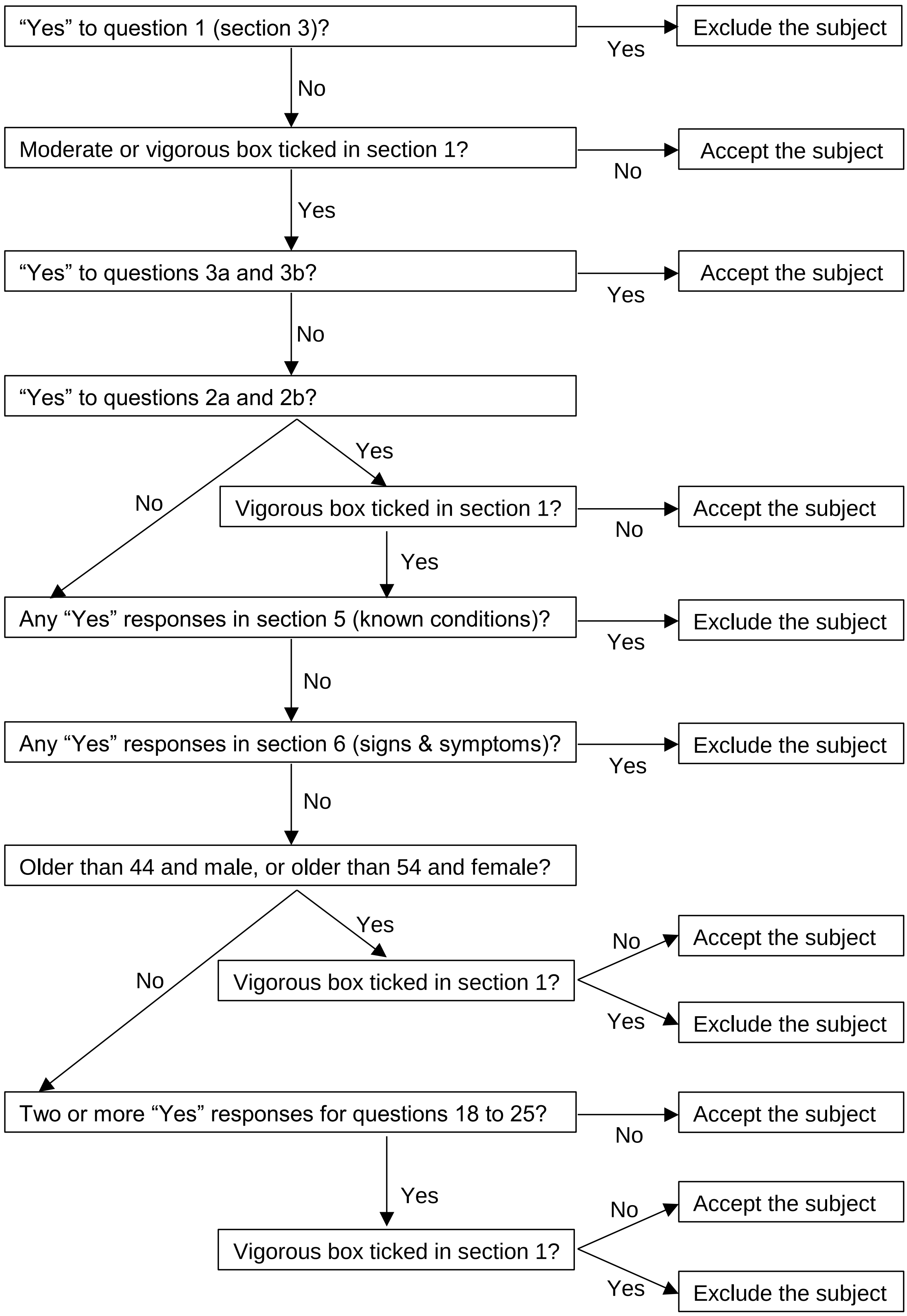
Section 10: Eligibility (to be completed by the tester)

26. Is the participant eligible for the testing? No Yes

Name (of tester): ....………..........……………………

Signature: ………………………………………………… Date: ………...……………...

Processing the completed questionnaire – a flow diagram



Preparing and processing pre-test health questionnaires

Introduction

These notes should be read in conjunction with the standard Health Questionnaire of the sport & exercise laboratories. They are intended to assist staff and students with a) preparing a health questionnaire for distribution to a potential participant and b) processing the completed questionnaire. The questionnaire is designed to gather the information needed to decide whether an individual is or is not eligible for a particular set of testing. This information is highly confidential and should be handled accordingly. During the course of a project or sequence of testing, it is the tester's responsibility to ensure that all completed health questionnaires are kept under lock and key and that the information they contain remains confidential. On completion of the project or sequence of testing, these questionnaires should be submitted to a technician, who will store them for 5 years for insurance purposes.

Preparing the questionnaire

First you need to summarise the cardiorespiratory demands of the testing by indicating whether it involves moderate or vigorous exercise. You should tick the moderate box for sub-lactate threshold exercise and the vigorous box for supra-threshold exercise or when testing is likely to invoke a marked cardiorespiratory response. For example, it would be appropriate to tick the vigorous box if the testing involves cold-water immersion, sustained isometric muscle actions or sustained exercise in an unusually hot or humid environment. If cardiorespiratory demands of the testing are minimal, you should not tick either box. However, if you are unsure you should err on the side of caution. Similarly, if you are unsure whether the exercise involved in a particular set of testing will be sub- or supra- threshold, tick the vigorous box. Next you need to summarise the musculo-skeletal demands of the testing by naming the activity and giving an indication of the forces involved in the testing so that the participant can make a judgement about whether any physical problem they have is likely to be aggravated. If you are unsure, err on the side of caution.

Processing the completed questionnaire

The process all laboratory users are expected to follow to reach a decision about whether a particular participant is eligible for testing is outlined below. This process is closely aligned with Olds and Norton's (1999) interpretation of the American College of Sport Medicine's Guidelines for Exercise Testing and Prescription (ACSM, 1995, 2000). It is underpinned by two key principles: first that the risk of a cardiac or other potentially fatal event occurring in response to exercise is low in individuals who are accustomed to meeting the cardiorespiratory demands of the exercise; second that the risk of such an event occurring in an unaccustomed individual depends on their age, whether they have particular medical conditions or show signs or symptoms of cardiovascular or pulmonary disease, and how many risk factors for cardiovascular disease they have. The process itself comprises a series of sequential steps.

1) Automatic exclusions

Question 1 covers blood-borne diseases, pregnancy, muscle or joint problems, recent fever or feeling unwell on the day. If the participant answers ‘Yes’ to any of the criteria they are automatically excluded.

2) Cardiorespiratory demands

Section 4 of the standard questionnaire summarises how often they typically exercise and when they last performed moderate or vigorous exercise. An individual should be deemed to be accustomed to a particular intensity of exercise if they typically experience it at least twice a week for moderate or once a week for vigorous exercise and have done so within the last 10 days. Individuals who show themselves to be accustomed to moderate exercise need to be screened further if the testing involves vigorous exercise but accept them if it involves moderate exercise. All participants are eligible for testing where the cardiorespiratory demands are minimal (for which neither the moderate nor the vigorous box would be ticked in section 1).

3) Known medical conditions

If there are any “yes” responses in section 5 exclude the participant, otherwise go to step 4.

4) Signs and symptoms of cardiovascular or pulmonary disease

If there are any “yes” responses in section 6 exclude the participant, otherwise go to step 5.

5) Age and sex

If the participant is older than 44 and male, or older than 54 and female, and the testing involves moderate exercise only, accept the participant or if the exercise is vigorous exclude the participant.

If they are younger than 45 and male, or younger than 55 and female, proceed to step 6.

6) Risk factors for cardiovascular disease

The tester should have completed section 9. To calculate the individual’s body mass index (BMI), divide their body mass in kg by their height in cm squared. A BMI of >30 kg/m^2 constitutes one risk factor. To classify the participant as sedentary or otherwise, use the information from section 4: a “no” response to question 2a **and** 3a constitutes one risk factor.

In section 7 and 9. if there is one or less “yes” response, accept the participant.
If there are two or more “yes” responses and the testing involves moderate exercise only, accept the participant or if it involves vigorous exercise, exclude the participant.

7) Signatures

Accepting or excluding a participant involves answering “yes” or “no” in section 10. Then print your name and sign and date the form. You then need to explain your decision to the participant.

It is sufficient for all participants (except those who report one or more signs or symptoms of cardiovascular or pulmonary disease), to provide a brief oral explanation of why they have been excluded. For those with two or more signs or symptoms, Appendix 8 contains a standard letter warning that the signs and symptoms listed on the questionnaire are not definitive indicators of disease and inviting the excluded participant to discuss with their GP the sensations or events they have reported.

Appendix 7 is a flow diagram showing how to process the completed questionnaire. The principle is that the processing stops when a decision to accept or exclude the participant can be made. Often this point will be reached after two or three steps. Performing all seven steps would only be necessary for testing involving moderate or severe exercise for which the potential participant is young and sedentary, with no known medical conditions or signs and symptoms.

Routine testing versus. specific projects involving special populations

Participants who would normally be excluded from a particular type of testing may be eligible provided the testing is conducted under medical supervision (e.g. in a cardiac rehabilitation programme). Projects involving high-risk populations, or vigorous exercise in moderate risk populations, involve medically qualified personnel and are most likely to be conducted in a hospital environment.

References

ACSM (1995). *Guidelines for Exercise Testing and Prescription* (5th ed.). London: Williams & Wilkins.

ACSM (2000). *Guidelines for Exercise Testing and Prescription* (6th ed.). London: Williams & Wilkins.

Olds, T.S. and Norton, K.I. (1999). *Pre-Exercise Health Screening Guide*. Leeds: Human Kinetics.

APPENDIX G
CONCENTRIC AND ECCENTRIC TORQUE VALUES PRE AND POST FATIGUE

Appendix G: Concentric and Eccentric torque values pre and post fatigue

	Pre			Post		
	0-10°	***10-20°***	***20-30°***	***0-10°***	***10-20°***	***20-30°***
Concentric Q at 60°/s	21 ± 7	32 ± 11	42 ± 11	14 ± 8	27 ± 12	36 ± 12
Concentric Q at 120°/s	18 ± 7	30 ± 8	37 ± 9	16 ± 5	23 ± 9	31 ± 11
Concentric Q at 180°/s	19 ± 6	28 ± 8	35 ± 9	18 ± 9	24 ± 9	30 ± 10
Eccentric H at 60°/s	33 ± 22	44 ± 20	52 ± 18	34 ± 18	47 ± 23	50 ± 25
Eccentric H at 120°/s	33 ± 21	46 ± 19	50 ± 17	24 ± 16	50 ± 23	54 ± 25
Eccentric H at 180°/s	31 ± 20	46 ± 19	51 ± 17	48 ±18	24 ±16	52 ± 21

Table 1: U13 Eccentric and Concentric torque pre and post fatigue by joint angle

Q = Quadriceps H = Hamstrings

Table 2: U15 Eccentric and Concentric torque pre and post fatigue by joint angle

	Pre			Post		
	0-10°	***10-20°***	***20-30°***	***0-10°***	***10-20°***	***20-30°***
Concentric Q at 60°/s	17 ± 9	33 ± 8	46 ± 10	18 ± 6	34 ± 12	46 ±10
Concentric Q at 120°/s	17 ± 6	33 ± 8	44 ± 10	19 ± 7	33 ± 8	42 ± 9
Concentric Q at 180°/s	23 ± 7	31 ± 8	40 ± 9	22 ± 6	31 ± 9	40 ± 8
Eccentric H at 60°/s	26 ± 9	51 ± 13	54 ± 13	23 ± 17	39 ± 21	45 ± 18
Eccentric H at 120°/s	30 ± 14	55 ± 10	57 ± 12	22 ± 11	44 ± 13	50 ± 12
Eccentric H at 180°/s	24 ± 15	50 ± 14	52 ± 13	22 ± 7	49 ± 14	52 ± 12

Q = Quadriceps H = Hamstrings

Table 3: U17 Eccentric and Concentric torque pre and post fatigue by joint angle

	Pre			Post		
	0-10°	***10-20°***	***20-30°***	***0-10°***	***10-20°***	***20-30°***
Concentric Q at 60°/s	26 ± 10	48 ± 15	62 ±17	24 ± 6	39 ± 9	42 ± 12
Concentric Q at 120°/s	24 ± 10	41 ± 13	54 ± 15	23 ± 7	33 ± 8	39 ± 9
Concentric Q at 180°/s	26 ± 9	39 ± 13	51 ± 15	25 ± 6	27 ± 10	33 ± 9
Eccentric H at 60°/s	35 ± 13	67 ± 21	71 ± 23	31 ± 19	85 ± 48	93 ± 43
Eccentric H at 120°/s	34 ± 15	75 ± 24	80 ± 20	25 ± 22	49 ± 34	66 ± 28
Eccentric H at 180°/s	30 ± 13	67 ± 27	77 ± 23	28 ± 28	65 ± 39	75 ± 28

Q = Quadriceps H = Hamstrings