SEX DIFFERENCES IN THE FUNCTIONAL HAMSTRING TO QUADRICEPS RATIO AND NEUROMUSCULAR PERFORMANCE

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A thesis submitted to
The University of Gloucestershire
In accordance with the requirements of the degree of
Doctor of Philosophy
In the Faculty of Applied Sciences

April 2012

ACKNOWLEDGEMENT

First of all, I am thankful to God the most Merciful for giving me the patience, perseverance and courage to finish this work. I would like to express my special gratitude to the following people whose assistance has made this thesis possible. My most sincere thanks to:

- My primary supervisor, Faculty Research Director, Reader in Sport and Exercise Physiology, Dr Mark De Ste Croix. Thank you for your most generous support, encouragement and guidance,
- My secondary supervisor, Deputy Dean, Faculty of Applied Sciences, Professor David James. Thank you for your expert guidance and advice,
- My third supervisor, Dr John Iga, for his thoughtful ideas during the initial "brain-storming" of studies,
- The research assistants who helped me during testing and for the support and encouragement.
- The test participants who most kindly participated in the research studies that constitute this thesis.
- The support of the individuals who constitute the Biomechanics Research Laboratory, and particularly David Williams and Mark Tabrett for their help and for providing invaluable technical support throughout.

This thesis is dedicated to my mother (Khamisa), my father (Omran), my wife (Abir), and my children (Arwa, Omran and Islam) who taught me what hard work and dedication can accomplish in life; my brothers and sisters for the everlasting prayer, love, support, and encouragement they have provided me with.

ABSTRACT

Increased relative risk of non-contact anterior cruciate ligament (ACL) injury has been attributed to numerous biomechanical, anatomical and neuromuscular factors. Females are at greater relative risk of non-contact ACL injury compared with males. Dynamic knee stability is an important component required to reduce relative risk of injury, especially to the knee joint. It is difficult to directly measure knee stability; however the eccentric ability of the hamstrings to co-contract to counter the torque produced by concentric quadriceps actions during knee extension is important in stabilising the knee (determined as the functional H/Q ratio [FH/Q]). One of the proposed reasons for a greater incidence of non-contact ACL injury in females is a reduced capacity for neuromuscular functioning to stabilise the knee joint effectively. Most injuries occur in the second half of an athletic event when fatigue is commonly present, therefore identifying fatigue as a potential risk factor for ACL injury and this may allow for the development of improved prevention strategies. The three experimental studies included within this thesis (chapter 4-6) have generated novel data on sex differences in the FH/Q ratio and neuromuscular performance prior to and following a downhill running fatigue task.

One hundred and ten healthy males (n=55; mean ± SD 29 ± 5 yrs) and females (n=55; mean ± SD 27 ± 6 yrs) were recruited from the university population. Isokinetic torque of the hamstrings and quadriceps was determined at 60, 120 and 240°·s^{-1}with the hip flexed at 0°. Range of movement of the knee joint was 90° with 0° determined as full volitional extension. Concentric (CON) torque was determined first followed by eccentric (ECC) torque, with the slowest velocity tested first. Torque was gravity corrected and filtered to only include constant velocity periods. For functional relevance FH/Q ratio was determined at 15, 30, 45º (as these are the joint angles where injury is most likely to occur) and where peak torque (PT) was achieved (to compare with the extant literature) for each movement velocity. Surface electromyography was recorded from the semitendinosus (ST), semimembranosus (SM) and biceps femoris (BF) of the dominant limb using an 8-channel DelSys EMG telemetry system. The biodex square wave synchronization pulse was configured with the EMG software via a trigger system so that EMG and torque data were completely time aligned. Raw EMG data were collected at a sampling frequency of 1024 Hz and included 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. The electromechanical delay (EMD) was determined as the time delay between the onset of muscle activation (change in activation of +15 µV) and onset of torque production (9.6 N·m) according to the procedures described by Zhou et al (1995).

The aim of the first study (chapter 4) was to explore sex differences in the FH/Q ratio whilst taking into account joint angle and movement velocity. A 2 (sex) x 3 (movement velocity) x 4 (joint angle) ANOVA was performed to determine interactions and main effects. FH/Q ratio ranged from 59 to 98% in females and 66 to 109% in males across joint angles and movement velocities. No significant differences between males and females in age but males were significantly taller and had greater body mass. Irrespective of sex the FH/Q ratio increased with joint angle and movement velocity to improve knee stability during high velocity movement and

near full extension. However, the FH/Q ratio is significantly lower in females compared with males and importantly this sex difference increases as movement velocity increases. Females have a lower FH/Q ratio than males close to full knee extension and during high velocity movements, both of which are predisposing factors for increased injury risk. This reduced FH/Q ratio may impair dynamic knee stability in females during fast velocity movements and may predispose them to a greater relative risk of knee injury.

The aim of the second study (chapter 5) was to examine sex differences in the EMD of the hamstring muscles during eccentric muscle actions at 60, 120 and $240^{\circ}\cdot s^{-1}$. A 2 (sex) x 3 (muscle group) x 3 (movement velocity) ANOVA was performed to determine interactions and main effects. During eccentric hamstring muscle actions there were no differences in the EMD of the 3 muscles examined. Irrespective of sex, significant main effects for angular velocity was demonstrated, indicating an increase in the delay time with increasing angular velocity. This increased delay during fast velocity movements may account for the increased risk of injury during fast movements. No significant sex differences in EMD was found irrespective of movement velocity of muscle examined, suggesting that females do not have impaired neuromuscular performance of the hamstring compared with males during eccentric hamstring muscle actions in the rested state.

The aim of the third study (chapter 6) was to examine the effects of a fatigue task on sex differences of the FH/Q ratio and EMD. The procedures used in study 1 and 2 were repeated pre and post a downhill running fatigue task to explore fatigue related effects on neuromuscular functioning. Each participant performed a 40 min intermittent downhill running protocol consisting of 5 × 8 min bouts on a -10% decline, with 2 min standing rest between each bout. Irrespective of sex, joint angle or angular velocity, the FH/Q ratio was lower and EMD of hamstrings muscle was longer post-fatigue compared to pre-fatigue. Significant interactions between sex and time (pre-post) for the FH/Q ratio and EMD of hamstring muscles were found. The interactions showed a significantly lower FH/Q ratio and significantly longer EMD post fatigue in females compared to males. These data suggest that functional stability of the knee is reduced when fatigue is present and the impact of fatigue is greater in females.

The findings of this thesis indicate the importance of determining the FH/Q ratio using angle specific torque as well as taking into account movement velocity, rather than simply using PT values to monitor muscle function of the knee. The findings of the present thesis support the notion that fatigue compromises the stability of the knee by reducing the FH/Q ratio and lengthening EMD. These effects are greater in females compared to males and may predispose them to greater relative risk of injury. Therefore, movement velocity, joint angle and fatigue resistance all need to be considered when designing training programmes to reduce the relative risk of injury. The focus of such training should be aimed at eccentric conditioning of the hamstring muscles to improve both muscular and neuromuscular functioning to limit the fatigue related effects, especially in females.

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Chapter 1:

Introduction

1-1 Introduction

Participation in physical activity has a range of physiological and psychological benefits, however it also carries a risk of injury (Bahr and Krosshaug, 2005). Non-contact anterior cruciate ligament (ACL) injury remains one of the more common knee injuries in sport, and both men and women experience ruptures to their ACLs (Kernozek et al., 2008). Injuries to the ACL occur in athletes participating in running sports requiring jumping and pivoting or landing from a jump (Arendt and Dick, 1995, McLean et al., 1999).The primary role of the ACL is to act as a restraint to anterior tibial displacement and forms an integral part of the hinge joint of the knee. Injuries to this stabilizing and mobilizing structure of the knee occur primarily in young, healthy individuals, most commonly as a result of sudden changes in direction or speed during physical activities such as sports (Hewett et al., 2007). Approximately 70% to 80% of sports-related ACL tears are "non-contact" injuries (Griffin et al., 2000, Hertel et al., 2004, Renstrom et al., 2008). This means that the injury occurs without making contact with another athlete (e.g., a tackle in football) or object (e.g a stick in field hockey).

With the increased participation of females in sports activities over the past decade, a dramatic increase in the rate of knee injuries involving the ACL has been documented (Arendt and Dick, 1995, Oliphant and Drawbert, 1996). Female athletes are known to have a higher risk of injuring their ACL while participating in competitive sports (Good et al., 1991). Compared with male athletes, female athletes are reportedly 4 to 6 times more likely to sustain a sports-related non-contact ACL injury (Arendt and Dick, 1995, James et al., 2004) even when differences in rates of participation and other obvious potential confounding factors are accounted for. Numerous risk factors as can been in figure 1 for non-contact ACL injuries have been identified in the literature (Hughes and Watkins, 2006), most of the evidence suggesting a relationship between potential risk factors and injury incidence is based on indirect/retrospective evidence. This is especially relevant for the intrinsic risk factors and those that are both modifiable and non- modifiable. Importantly, the evidence of a relationship between neuromuscular performance capability, fatigue and injury incidence remains to be directly established.

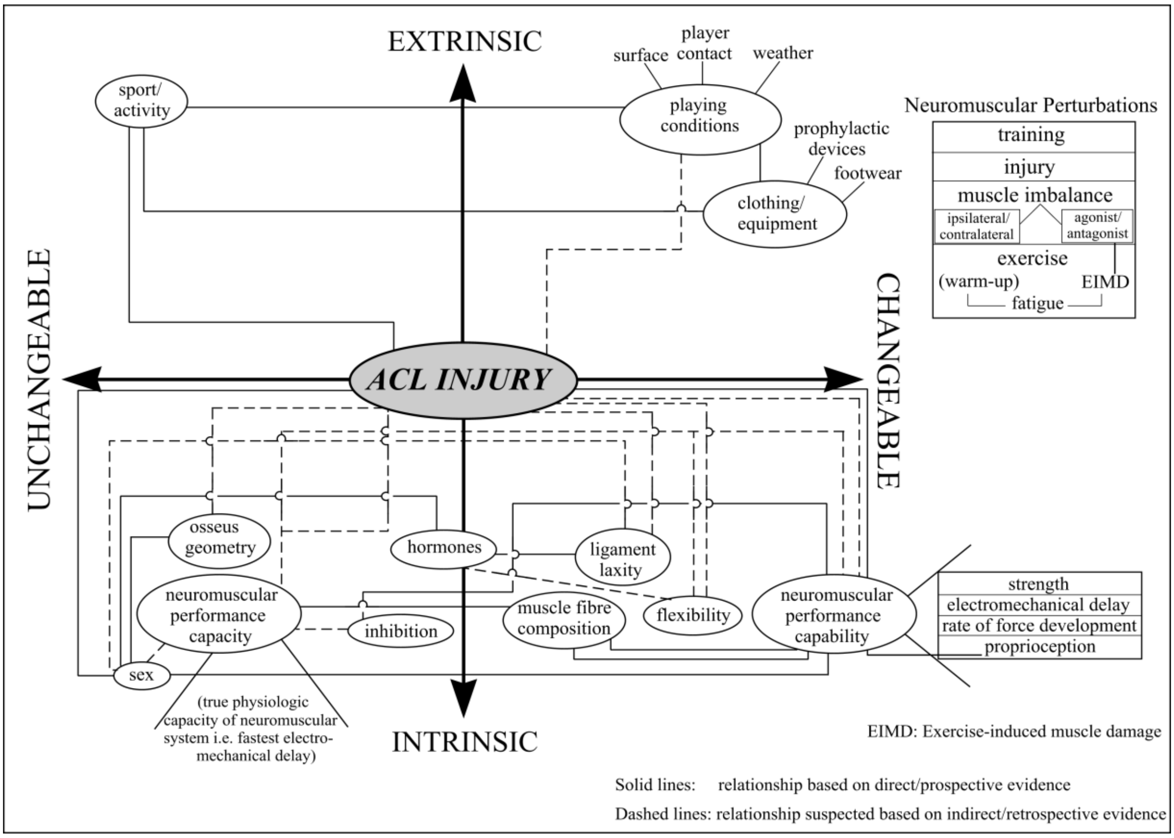


Figure (1) illustrating a conceptual model of anterior cruciate ligament (ACL) injury (taken from Minshull, 2004).

Not surprisingly the focus of these mechanisms has been on potentially modifiable risk factors relating to body positioning, joint loading, and neuromuscular coordination in preventing and reducing the incidence of this injury. However, it is acknowledged that there is probably a number of non-modifiable risk factors that predispose females to this greater relative risk of injury that includes anatomical (e.g intercondyle notch width) and biological (hormones) risk factors. Therefore the desire to elucidate the factors attributable to sex differences in ACL injury rate has led to many studies attempting to elicit physiological, hormonal, and anatomical variances that may predispose females to ACL injury (Loudon et al., 1996, Shelbourne et al., 1998, Wojtys et al., 1998, McLean et al., 1999). Sex differences in neuromuscular control and biomechanical function are thought to be primary factors that may account for this sex bias (Griffin et al., 2000). Unfortunately, to date, our understanding of the mechanisms that predispose women to a greater relative risk of ACL injury is unclear.

Dynamic knee stability is the ability of the knee joint to remain stable when it is exposed to the rapidly changing loads that occur during activity (Williams et al., 2001). Dynamic stability of the knee plays an important role in reducing the relative risk of injury from a muscular and neuromuscular perspective. At decreased joint angles decelerating manoeuvres involve the dynamic stabilisers to maintain joint stability (Wikstrom et al., 2006) since static restraints efficiency is reduced at this point (Senter and Hame, 2006). During knee extension the quadriceps contract powerfully and increase tibial rotational and anterior shear (Griffin et al., 2006). An adequate response to this situation is hamstrings co-activation, which decreases the strain on the ACL between 0.35 and 1.05 rad of knee flexion (Senter and Hame, 2006). However, when joint stiffness is required near full knee extension both quadriceps and hamstrings are in an unfavourable position to perform their function, and this can be observed in the action-specific length-tension relationships. Fast knee extension movements also appear to be a risk factor since the effectiveness of dynamic stability depends on their biomechanical and physiological characteristics which are impaired by the requirements of the velocity of movements as can be seen in their torque-velocity relationships.

Muscular forces are crucial in maintaining joint stability predominantly by increasing joint stiffness through co-contraction. In vivo exploration of hamstring or quadriceps co-contraction suggests that it doubles or even triples joint stiffness and decreases joint laxity by up to 50% (Russell et al., 2007). Data from adults indicate that sidestepping and cutting movements are most likely to load the ACL and subsequently increase the relative risk of injury (Lloyd et al., 2005). In addition, the use of neuromuscular biomechanical modelling to understand knee ligament loading and subsequent knee joint stability has emphasised the importance and effectiveness of the muscles in providing this stabilisation (Lloyd et al., 2005). During landing, when potential to injure the ACL exists, the response of the neuromuscular system is critical. The ACL can provide up to 86% of the resistance to anterior tibial translation, however it is well recognised that the internal and external forces incurred at the knee during landing stresses the passive ligament structures beyond their capacity.

Most injuries happen in the second half of an athletic event when fatigue is commonly present (Hertel et al., 2004), and fatigue is suggested to be a factor in injury risk for both males and females. The functional hamstring to quadriceps ratio (FH/Q) may be associated with injury risk to the knee, and this assertion would be further supported if the ratio was reduced in the fatigued state. Fatigue-related changes in neuromuscular performance also may be interpreted to represent an increased risk of injury (Chan et al., 2001, Gleeson et al., 1998b, Mercer et al., 1998). Therefore, identifying fatigue as a potential risk factor for

ACL injury, and exploring the interaction between fatigue and other potential risk factors, may allow for the development of improved prevention strategies.

Evaluation of isokinetic eccentric antagonistic strength relative to concentric agonist strength may be of value in describing the maximal potential of the antagonistic muscle group (Coombs and Garbutt, 2002). The hamstring to quadriceps ratio has conventionally been expressed as concentric hamstrings to concentric quadriceps strength (Lund-Hanssen et al., 1996) which does not reflect the *functional* capacity of the knee during dynamic movement. A FH/Q ratio of about 1.00 has been reported for fast isokinetic knee extension movement, indicating a significant capacity of the hamstring muscles to provide dynamic joint stabilisation during active knee extension (Aagaard et al., 1998). A number of studies have now started to report the functional ratio but are mainly limited as they use peak torque (PT) which tends to occur in the mid-range of the movement rather than near full knee extension where injury is likely to occur. Studies also tend to use PT obtained from CON and ECC actions that do not occur at the same joint angle and therefore tells us little about co-contraction and is thus not functionally relevant. The FH/Q ratio is also velocity and joint angle dependent (Aagaard et al., 1998). The current study builds on the work of Sauret et al., (2009), who suggested that the functional ratio should be calculated at specific joint angles to avoid differences in PT between quadriceps and hamstring due to varying joint angle. The sample size of related previous studies is also limited and there are few studies that have used female participants. Another limitation of previous studies is that hip position has not been taken into account and all available studies appear to have tested in a sitting position which is not relevant to sporting activities. This is particularly important as we know that torque appears to be significantly greater for knee flexion in a sitting position when compared to the more ecologically valid supine or prone position

(Black et al., 1993). An advantage of the assessment of torque in the prone and supine position, is that it provides a closer approximation of the length tension relationship of the hamstring and quadriceps muscles during many functional and sporting activities, and is therefore functionally relevant (Worrell et al., 1990). The exploration of sex differences in the FH/Q ratio, taking into account functionally relevant hip joint angle and using a range of movement velocities, remain to be investigated, particularly in a fatigued state, and might reflect predisposition to injury.

High levels of neuromuscular control are also necessary to create dynamic knee stability (Besier et al., 2001). Neuromuscular pre-planning allows feed forward recruitment of the musculature that controls knee joint positioning during landing and pivoting manoeuvres (Besier et al., 2001). Imbalanced or ineffectively timed neuromuscular firing (including feedback mechanisms) may lead to limb positioning during athletic manoeuvres that puts the ACL under increased strain and increases the risk of injury (Myer et al., 2005b). It has been suggested that females display a longer latency period than males between preparatory and reactive muscle activation (Winter and Brookes, 1991). The electromechanical delay (EMD), which is defined as the time delay between the onset of muscle activity and onset of joint acceleration (Norman and Komi, 1979), may be associated with the unrestrained development of forces of sufficient magnitude to damage ligamentous tissue during prolonged exercise (Winter and Brookes, 1991). Sex differences in muscle recruitment and timing of muscle activation may affect dynamic knee stability (Hewett et al., 2005). It has previously been suggested that EMD will vary substantially due to the characteristics of the muscles being tested (e.g. architectural arrangement and fibre type distribution) (Viitasalo and Komi, 1981); muscle action (e.g. eccentric, concentric, voluntary, reflexive) (Norman and Komi, 1979, Zhou et al., 1995); and data processing techniques (Corcos et al., 1992). However, a limited number of studies have investigated the influence of movement velocity on EMD, and only one during eccentric actions (Ronald et al., 1998). This is surprising given the range of movement velocities produced during sporting performance and that non-contact ACL injury may be velocity dependent. To date no studies appear to have examined sex differences in EMD of the hamstrings under eccentric conditions during knee extension movements, let alone under conditions of fatigue.

Most of the literature to date evaluating the effect of fatigue on neuromuscular reflex behaviour has been conducted almost exclusively on males. While there are a few studies that have examined sex differences and EMD (Bell and Jacobs, 1986, Zhou et al., 1996, Winter and Brookes, 1991) and found EMD to be longer in females than males, no studies have explored neuromuscular reflex behaviour at the knee as a function of both sex and fatigue during eccentric actions. Whether EMD contributes to the greater relative risk of non-contact ACL injury in females is unclear as further research is needed to explore the sex related changes in EMD, especially during eccentric actions of the hamstrings at a range of velocities, and when fatigue is present.

For the FH/Q ratio, if the hamstrings eccentric PT is equal to the peak concentric quadriceps torque then the ratio is 1:1 and the joint is supposedly not at risk whereas if the quadriceps are stronger, then the ratio is less than 1, and the joint is considered at risk (Hughes and Watkins, 2006). A FH/Q ratio of less than 0.6 has been linked with a 17-fold increase in the relative risk of hamstring injury (Yeung et al., 2009). Nevertheless, it may be hypothesised that, in the fatigued state, the FH/Q ratio would be less than in the non-fatigued state if it is to be considered that the FH/Q ratio mediates the link between fatigue and injury risk of the knee. Although fatigue has been proposed to increase the risk of ACL injury (Hertel et al., 2004), there is currently no evidence to suggest that fatigue has a greater effect on the incidence of ACL injury in females compared with males (Hughes and Watkins, 2006). However, most injuries occur in the second half of an athletic event (Hertel et al., 2004) when fatigue is commonly present. Identifying fatigue as a potential risk factor for an ACL injury may allow for the development of improved prevention strategies. Furthermore, no studies have investigated sex differences in either muscular or neuromuscular knee stability, focusing on eccentric actions of the hamstrings, following a field based fatigue task.

Therefore, this thesis proposes to examine sex differences in muscular performance (FH/Q ratio) and neuromuscular (EMD) performance of the hamstrings muscle that appear to be associated with reduced knee stability and an increased risk of ACL injury. Additionally it will also investigate sex differences in the FH/Q ratio and EMD following a field based fatiguing task.

1-2 Aims and objectives of thesis

The following chapters will investigate variables that may be important in understanding potential risk factors for ACL injury. Therefore, the aims of the studies that comprise the present thesis will be accomplished through answering the following questions:

1- What are the differences in the FH/Q ratio between males and females?
2- What are the differences in the neuromuscular performance (EMD) of the knee flexor muscles during eccentric actions between males and females?
3- What are the effects of a fatigue task on FH/Q ratio and EMD of the knee joint muscles in males and females?

Chapter 2:
Literature Review

2.1 INTRODUCTION

The total number of teams sponsored by the United States National Collegiate Athletic Association (NCAA) institutions (men and women combined) increased 20.2%, from 12,447 in 1987-88 to 15,582 in 1997-98. At the same time, the total number of student-athletes rose 20.7%, from 268,776 to 338,866. Much of this increase can be attributed to the significant growth in women's intercollegiate sports. While the number of male teams and student-athletes rose only 12.0% and 12.3%, respectively, female athletic teams and student-athlete participation increased by 27.8% and 33.6% respectively. During this ten-year span, three new women's sports were recognized (ice hockey, rifle, and water polo), and female participation in golf, rowing, skiing, and soccer increased over 50% (National-Collegiate-Athletics-Association, 2004). During this same period of time, non-contact injuries to the anterior cruciate ligament (ACL) in physically active females increased proportionately. Each year, it is approximated that 80 000 to 250 000 ACL injuries occur in young athletes as increasing numbers of participate in sports (Griffin et al., 2006). The number of female ACL injuries also will to continue to grow as increasing numbers of females participate in sports.

The non-contact ACL injury remains one of the more common knee injuries in sport, and both men and women experience ruptures to their ACLs (Kernozek et al., 2008). Colby et al. (2000) reported that 70% of all ACL injuries are sport related. ACL injury rates differ by sex in several sports, with women experiencing two to eight times higher injury rates than men in the same sports (Good et al., 1991). A limited number of studies that have investigated the possible reasons of the incidence of ACL injury based on time at risk and compared male and female athletes competing in similar activities at the same level of competition (Renstrom et al., 2008). Most injuries happen in the second half of an athletic event when fatigue is commonly present (Hertel et al., 2004), and fatigue is known to be a factor in injuries to both males and females.

Actions of the knee joint are known to involve a combination of rolling and gliding movements. Knee joint stability is known to be an important factor in risk of injury (Blackburn et al., 2009). Dynamic knee stability is also known to be important, and high levels of neuromuscular control are a requirement for dynamic knee stability (Besier et al., 2001). When high loads are placed on the ligaments and other soft tissues, for example during high speed sport activities, additional stabilizing forces are required to keep the strain in knee ligaments within safe ranges. The activation of the antagonist muscle provides a stabilising force, but is known to be reduced as the movement pattern becomes more familiar, resulting in increased efficiency of movement (Solomonow and Krogsgaard, 2001). The functional hamstring to quadriceps ratio may be associated with injury risk to the knee, and this assertion would be further supported if the ratio was reduced in the fatigued state.

This review of literature is divided into five sections. The first section will review the incidence and risk factors of ACL injury. The second section will discuss functional knee stability. The third section will consider the importance and assessment of the functional ratio. The fourth section will address electromyography (EMG) and the last section will discuss fatigue and its role in force production and neuromuscular control.

2.1.1 Anterior cruciate ligament (ACL) injury

Injury can be described in terms of its severity. Injury severity is usually classified according to the length of time needed for recovery. Van Mechelen et al. (1992) recommended the following expanded criteria to account for the degree of injury severity: type of injury, length of treatment, absence from training and game, work disability, structural and permanent changes to the body, costs of injury.

Anterior cruciate ligament injury has been increasingly problematic in the lives of both recreational and competitive athletes, both physically and psychologically (Mandelbaum et al., 2005). Injuries to the ACL are frequent in athletes participating in running sports requiring jumping and pivoting (Arendt and Dick, 1995). The ACL role is primary to hold the knee intact and forms an integral part of the hinge joint of the knee. Injuries to the stabilizing and mobilizing structure of the knee occur primarily in young, healthy individuals, most commonly as a result of sudden changes in direction or speed during physical activities such as sports (Hewett et al., 2007). An ACL tear is most frequently a sports-related injury. ACL tears can also occur during rough play, motor vehicle collisions, falls, and work-related injuries. About 80% of sports-related ACL tears are "non-contact" injuries (Griffin et al., 2000, Hertel et al., 2004, Renstrom et al., 2008). This means that the injury occurs without making contact with another athlete (e.g., a tackle in football). Most often ACL tears happen when pivoting or landing from a jump (McLean et al., 1999). Female athletes are known to have a higher risk of injuring their anterior cruciate ligament while participating in competitive sports (Good et al., 1991). Unfortunately, to date, complete understanding as to why women are more prone to ACL injury is unclear.

2.1.2 Incidence of ACL injury

Incidence and prevalence are the two common frequency rates, which have been reported in the sport injury literature (Powell et al., 1986). Prevalence rates concern the total number of cases, new or old, that exists in a population at risk at a specific period of time. Incidence rates concern the number of new injuries that occur in a population at risk over a specific period of time (Hunter, 1988). Each year, it is approximated that 80 000 to 250 000 ACL injuries occur in young athletes (Griffin et al., 2006). Up to two-thirds of patients who have complete ACL tears develop knee instability and, subsequently, damage to the menisci and articular surfaces, which significantly affects knee function and leads to a decrease in level of activity (Smith et al., 1993, Keene et al., 1993). Hughes and Watkins, (2006) found that in a group of individuals with rupture of the ACL, 31% of patients reported overall difficulty in walking alone, 44% had difficulties with activities of daily living including walking, and 77% had difficulties with playing sport as a direct result of their ACL injury (Griffin et al., 2000).

Arendt and Dick, (1995) reported the incidence of ACL injury in United States collegiate basketball and soccer for males and females over the period 1989-93. Data were collected for 461 male and 278 female soccer teams and 531 male and 576 female basketball teams. ACL injury was reported in terms of athlete-exposure, where athlete-exposure took into account games and practice sessions. For soccer, female injury incidence was 0.39 per 1000 athlete-exposures compared with 0.13 per 1000 athlete-exposures for males. For basketball, the incidence of ACL injury was 0.29 per 1000 athlete-exposures for females and 0.07 per 1000 athlete-exposures for males. Malone et al. (1993) documented the injuries of 402 male and 385 female basketball players from 29 institutions in three division one United States collegiate basketball conferences over a 5-year period. Sixtytwo females and nine males sustained ACL injury, which corresponded to an incidence of 16.1% in females and 2.2% in males.

Inklaar (1994) reported an overall analysis of incidence rate from different studies, ranging from 0.5 to 45 ACL injuries per 1000 hours of games and training. The incidence of reported injuries varies due to different methods of data collection, study design and sample characteristics, as well as different definitions for injury. Hawkins and Fuller (1999) reported the ACL injury incidence (the ratio of the injuries recorded to the number of players taking part in all the matches analysed, expressed as a percentage) of 27.7% per player for all injuries in 44 games played and injury frequency rate (number of injuries per 1000 hours of competition or training) of 6880 injuries per 100 000 hours played. With respect to injuries, which resulted from player contact, Hawkins and Fuller (1996) reported that 64% of observed injuries were as a result of contact injury, which is in agreement with Hoff and Martin (1986) who reported 66% and 52%, respectively.

De Loes et al. (2000) studied cruciate ligament injury (ACL and posterior cruciate ligament “PCL” combined) in Swiss youth enrolled in a national youth sport programme (ages 14-20), where approximately “370,000” youth participate in the programme. Over a seven-year period, a total of 470 ACL/PCL injuries were reported (annual average of 67 injuries). The incidence rate for females was 0.52 per 100,000 athlete-hours. For male, the rate was 0.62 per 100,000 athlete-hours. Annually, there was approximately one ACL or PCL injury per 5000 participants. Males accounted for 76% of the ACL/PCL injuries. On the basis of these data, it is reasonable to state that the incidence in the general population is low. However, even accounting for low incidence rates, the burden on the health systems is high. For example, De Loes et al. (2000) found that ACL/PCL injury in the study population had the highest average cost of all knee injuries. More males than females sustain an ACL injury caused by the greater absolute number of male participants in sport activities (Griffin et al., 2000). However, the risk of sustaining an ACL injury is reported to be two to eight times higher among female athletes compared to male counterparts (Arendt and Agel, 1999, Griffin et al., 2000, Hewett et al., 1999, Myklebust et al., 1998, Roos et al., 1995). Females also appear to obtain injuries at a younger age than men (Roos et al., 1995). A previous study found small sex differences in the overall risk of sustaining an ACL tear and sex differences in injury rates persisted when specific sports were compared (Mountcastle et al., 2007).

For each team, the average injury incidence of moderate (see below for explanation) injury is estimated to be 113 per 1000 game hours (Hawkins and Fuller, 1996) and 300 per 1000 game hours (Ekstrand et al., 1983). Hawkins and Fuller (1999) later reported 8.5 injuries per 1000 hours over three seasons of competition. Ekstrand et al. (1983) estimated that the incidence of injury for an indiviual player during a year was 7.6 per 1000 practice hours and 16.9 per 1000 game hours. They reported that 256 injuries occurred among the 180 players during the year, that 62% were minor injuries (absence from practice of less than one week), 27% moderate injuries (absence from practice of more than one week but less than one month), and 11% major injuries (absence from practice of more than one month). Nielsen and Yde (1989) found the injury incidence of all players was 3.6 per 1000 practice hours and 14.3 per 1000 game hours. Engstrom et al. (1991) reported that for players who participated in soccer competition for one year, the incidence of injury was 24 per 1000 hours during the game, and 7 per 1000 hours during training. Approximately two-thirds of injuries occur during competition and one-third during training. This proportion has been demonstrated in several investigations (Sullivan et al., 1980, Albert, 1983, Ekstrand et al., 1983, Nielsen and Yde, 1989).

In an active German population the general ACL injury incidence was 70 per 100 000 citizens in the more physically active proportion of the population. In Sweden the occurrence of ACL injury in the population aged 10–64 years was 81 per 100 000 citizens (Renstrom et al., 2008). Due to the high intensity of activity in competition, it would be expected that more injuries occur during cometition than in traning. With respect to incidence rate and level of competiton, Nielsen and Yde (1989) found a direct relationship between injury incidence rate and the level of competition with the higher incidence rate associated with the higher level of intensity of play. In contrast, Hawkins and Fuller (1998) reported that there is no relationship between injury incidence rate and level of competion. The weight of evidence suggests that players who play at a high level of intensity can expect to sustain more injuries than players who take part in competitions at a lower level.

In looking at a possible difference between the sexes, in 2005–2006 the Swedish Registry found a higher proportion of both primary ACL reconstructions and revisions in men than in women (59% vs. 41% and 55% vs. 45%, respectively) (Renstrom et al., 2008). However, there is consensus in the literature that female athletes have a greater risk of incurring an ACL injury than male athletes when they compete in the same sport at the same level of competition. However, most studies have focused on the prevalence of ACL injuries associated with high-risk sports; only a limited number have calculated the incidence of ACL injury based on time at risk and compared male and female athletes competing in similar activities at the same level of competition (Renstrom et al., 2008).

In summary, numerous studies have found that the incidence of sports-related anterior cruciate ligament (ACL) non-contact injuries has increased substantially over the past 30 years and that women in sports involving jumping and cutting movements are at higher risk for non-contact ACL ruptures than the men involved in those same sports even when differences in rates of participation and other obvious potential confounding factors are accounted for (Agel et al., 2005, Gwinn et al., 2000). However, to understand fully the risk of injury that a player is exposed to in the sport, it is necessary to analyse the key factors in the game and to relate these factors to the risk they may present and the subsequent injuries which may result from them. For example, most injuries occur in the second half of an athletic event (Hertel et al., 2004), when fatigue is commonly present. One study has also demonstrated that the FH/Q ratio is compromised at the end of each half of a football match, indicating that fatigue effects are present during the last half of the match (Small et al., 2010). Identifying fatigue as a possible risk factor for an ACL injury may allow for the development of improved prevention strategies.

2.1.3 Mechanisms of non-contact knee injury

The mechanism of ACL injury is a main focus of discussion in the injury literature, as an ACL tear is more often a non-contact event (Renstrom et al., 2008). Injuries to the ACL that happen without physical contact between athletes are referred to as non-contact ACL injuries (Feagin and Lambert, 1985, Ferretti et al., 1992) and most occur where sudden deceleration or a change of direction, landing and pivoting manoeuvres are repeatedly performed (Yu and Garrett, 2007).

To produce specific interventions for preventing sports injuries, it is important to understand the causative event or mechanism of injury, as outlined by Krosshaug and

Bahr, (2005b). Many different methodological approaches have been used to study the mechanisms of injury in sports (Krosshaug and Bahr, 2005b). Video analysis is necessary as it is usually the only way to obtain kinematic information from the actual event. In rare cases, injuries have even occurred through biomechanical experiments, but for obvious ethical reasons it is difficult to base any research on this as a prospective approach. Six studies have used video analysis to study non-contact ACL injury mechanisms in sports and have been summarised in Table 1.

Table 1- Studies using video analysis to investigate mechanisms of non-contact ACL injury

References	No. of games	No. of ACL injuries	Methods
Boden et al., (2000)	27	15	Visual inspection and questionnaires. Videos obtained from professional and collegiate teams: football (56%), basketball (30%), soccer (9%), volleyball (4%). 7 women, 16 men.
Ebstrup and Bojsen-Moller, (2000)	15	3	Visual inspection. Prospective collection of videos from Danish indoor ball games. Two representative handball injuries and one basketball injury analysed. All women.
Teitz (2001)	54	14	Visual inspection. Retrospective multicentre video analysis: 20 basketball, 18 football, 9 soccer injuries. Only basketball injuries analysed. 3 men, 11 women.
Krosshaug, et al., (2007a)	20	19	Visual inspection and questionnaires. Retrospective and prospective video collection of women's Norwegian or international handball competition
Krosshaug et al., (2007b)	39	30	Visual inspection. Retrospective video collection from high school, college and NBA, WNBA basketball. 13 men, 17 women.

These studies were in general agreement that injuries predominantly occur in cutting or landing situations. The knee joint was reported to be relatively straight (extended) at the point of injury. Boden et al., (2000) found that the amount of internal/external rotation at the time of rupture was minimal. This agrees with the findings of Olsen et al. (2004) where the amount of internal/external knee rotation was 10° or less in 90% of the cases. However, the interpretation of the result varied considerably. Olsen et al., (2004) stated that valgus loading in combination with external or internal knee rotation caused the injury and proposed notch impingement as a plausible cause of the excessive ACL loading. Boden, et al., (2000) and Teitz (2001), on the other hand, hypothesised that a vigorous eccentric quadriceps contraction was the main cause.

The traditional marker-based motion analysis method provided average hip flexion and knee flexion/extension data. Krosshaug et al., (2007c) demonstrated the feasibility of these method using actual injury videos. Detailed time courses for joint kinematics and ground reaction force were obtained from a four camera basketball video and a three-camera handball video. The valgus angle increased abruptly in both injury cases, from 4° to 15° within 30 ms and from 3° to 16° within 40 ms for the basketball and handball injury, respectively. However, to make generalisable statements on typical injury kinematics, a systematic approach to collecting and analysing more injury videos is needed.

Table 2- Activities Reported at the Time of Non-Contact ACL Injury

Reference	Total observed sample	Decelerating from running without changing direction	Decelerating from running with changing direction	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%

Mechanisms of ACL injury have been investigated by interviewing those who have sustained an ACL injury (Table 2) (Boden et al., 2000, Fauno and Wulff Jakobsen, 2006, Ferretti et al., 1992, Olsen et al., 2003). Most of the injuries are reported to occur with non-contact mechanisms, such as those involving landing from a jump and sudden deceleration of the body while running, with or without a change in direction (Ferretti et al., 1992, Olsen et al., 2003, Fauno and Wulff Jakobsen, 2006). A general characteristic in these retrospective self-report studies is that ACL-injured individuals often report that the knee moves in multiple planes of motion (Ferretti et al., 1992; Olsen et al., 2003).

An additional important characteristic appears to be the knee flexion angle at the time of injury. Although one group (McNair et al., 1990) reported that the ACL injury occurred when the knee was at or near full extension, knee hyperextension is also often reported as part of the mechanism (McNair et al., 1990, Boden et al., 2000). Also, the majority of non-contact ACL injuries were reported to happen during weight-bearing conditions (Boden et al., 2000, Fauno and Wulff Jakobsen, 2006, Ferretti et al., 1992, Olsen et al., 2003), a finding supported by Fauno and Wulff Jakobsen (2006) who noted that 104 of 105 ACL-injured patients stated that the injury happened when the foot associated with the injured limb was in contact with the ground. Even with these research design limitations, important information about the mechanisms of ACL injury has been gained. From these reports, non-contact injury may be more likely when the knee is in a shallow flexion angle (McNair et al., 1990) or a hyper-extended position (Boden et al., 2000), and the repeatedly observed combined motions in both frontal and transverse planes during sudden deceleration motions indicate that ACL injury likely results from multi-plane knee loading (Boden et al., 2000, Fauno and Wulff Jakobsen, 2006, Ferretti et al., 1992, Olsen et al., 2003).

Recent studies have consistently demonstrated that the predominant forces that affect strain in the ACL are anterior-directed shear forces applied to the tibia (either from external sources such as an anterior-directed force applied to the back of the lower leg or through internal mechanisms such as contraction of the dominant quadriceps muscles with the knee near full extension) (Berns et al., 1992, Arms et al., 1984). Important contributions to ACL strain values come from forces applied in the coronal and transverse planes of the knee (Renstrom et al., 2008). External torque applied to the knee creates relatively low ACL strain values. Valgus torque alone creates ACL strain only after significant injury to the medial collateral ligament. Interestingly, complete injury to the MCL was essential before significant injury to the ACL resulted from valgus torques applied in isolation (Mazzocca et al., 2003). These cadaver studies emphasise the importance of anterior shear forces in ACL injury (Renstrom et al., 2008).

In summary, most of the knee injuries are reported to be a consequence of non-contact mechanisms, such as those involving landing from a jump and sudden deceleration of the body while running, with or without a change in direction (Ferretti et al., 1992, Olsen et al., 2003, Fauno and Wulff Jakobsen, 2006). Fatigue may have an influence on such mechanisms and affect men and women differently. Under fatigued conditions, it was shown that males and females decrease knee flexion angle and increase proximal tibial anterior shear force and knee vagus moments when performing stop-jump tasks (Chappell et al., 2005). Decker et al., (2003) reported that women land with a more erect posture and rely on the ankle plantar flexors to transmit forces proximally. They hypothesized that, in a fatigued state, this landing strategy exhibited by the female subjects will place them at an increased risk of knee injury because the fatigue will further inhibit the muscles ability to stabilize the knee (Decker et al., 2003). The potential role of fatigue in knee injury mechanisms, and the relative influence in males and females, requires further investigation.

2.1.4 Factors increasing relative risk of knee injury

It has been well documented in the literature that injuries about the knee have a high incidence compared to injuries in general, and multiple studies have found anterior cruciate ligament (ACL) ruptures to have high incidence of associated problems (e.g., meniscal tear) (McKinney et al., 2008). The risk of ACL injury is affected by a number of factors; these factors need to be understood to devise effective preventive strategies. In the literature, three different classification schemes have been used when discussing risk factors for non-contact ACL injury. In the first, risk factors are divided into extrinsic factors which concern environmental conditions and the manner in which activities are administered (those outside the body) and intrinsic factors that distinguish individuals from each other (those from within the body) (Murphy et al., 2003). In the second scheme, Griffin et al. (2000) categorised risk factors into three intrinsic groups (anatomical, hormonal and biomechanical) and one extrinsic group (environmental). While these categories may be of some help in identifying the possible cause of an injury, in most cases the cause of the injury is likely to be the result of a complex interaction of intrinsic and extrinsic factors (Lysens et al., 1984). The third scheme, which has been selected as the basis of the present review, divides risk factors into the following four categories: environmental, anatomical, hormonal, and neuromuscular/biomechanical (Perrin and Shultz, 2005, Griffin et al., 2006). It is important to reinforce that the evidence linking most risk factors to injury incidence is linked and the suspected relationship between factors and injury tend to be based on indirect evidence.

2.1.4.1 Environmental risk factors

Environmental (external) factors comprise meteorological conditions, the type of surface (grass, hard floor, etc), the type of footwear and its interaction with the playing surface, and protective equipment such as knee braces (Griffin et al., 2006). Limited concentration has been directed toward the potential influence of weather conditions on injury during competition (Griffin et al., 2000, Orchard and Powell, 2003). The majority of injuries occurred during conditions of no precipitation and low humidity, therefore minimizing the opportunity to thoroughly ascertain possible influences of various field conditions.

A small cohort study of eight high school football teams in Texas noted an approximately 50% reduction in the rate of ACL injury on the latest generation of artificial turf, relative to natural grass. Meyers and Barnhill, (2004) recorded only 14 ACL injuries and did not include data on type of footwear worn or the traction of the surface (Meyers and Barnhill, 2004) so this finding must be interpreted with caution. Meyers and Barnhill, (2004) attempted to quantify weather conditions at time of injury, showing that the majority of injuries happened during dry conditions, warm temperatures, and low humidity. Conditions of no precipitation (dry surface) were related with 201 (88.3%) injuries on Field Turf and 106 (84.4%) of injuries on natural grass. Rain or wet field conditions were connected with 27 (11.7%) trauma cases on Field Turf and 19 (15.6%) on natural grass. No injuries were reported during snow or sleet conditions. Although no significant differences were noted between playing surfaces across temperature, interestingly, when analyzing data by cold days as compared to hot days, as suggested by Orchard and Powell, (2003), a significantly higher incidence of injury was observed during hot days on FieldTurf as compared to natural grass. On cold days, the occurrence of injury was similar on both surfaces.

Regarding footwear, Lambson et al., (1996) found that the risk of suffering an ACL injury is greater in football athletes who have boots with a higher number of studs and an associated higher torsional resistance at the foot-turf interface. Earlier studies suggested that shorter studs of footwear design length were associated with a reduced risk of knee and ankle injuries (Lambson et al., 1996, Robey et al., 1971). However, in recent years, there has been limited laboratory-based experimental or epidemiologic research addressing footwear and its interaction with the type of playing surface, possibly because of the complexity of this relationship, which may be further modified by intrinsic factors (Griffin et al., 2006). It is quite probable that increased shoe-surface traction is a direct risk factor for ACL injury, but it should also be noted that athletes modify their movement patterns to adapt to variations in shoe and surface factors and thereby may alter neuromuscular and biomechanical factors that influence ACL injury risk (Milburn and Barry, 1998).

Sitler et al., (1990) found that prophylactic knee brace use was associated with a reduced rate of knee injury. This large epidemiologic study focused on football but did not examine ACL injury specifically (Albright et al., 1994). The biomechanical confirmation of the effect of prophylactic knee braces on the ACL injury risk remains equivocal (Najibi and Albright, 2005). A controlled laboratory study on a latest functional knee brace with a constraint to knee extension established that the new knee brace significantly increased knee flexion angle in a stop-jump task (Yu et al., 2004).

In summary, the evidence base regarding environmental factors is confusing and mixed. The few methodologically rigorous studies that have been achieved are limited by small numbers of ACL injuries . It appears plausible that harder surfaces and shoes with longer studs increase shoe-surface traction and the risk of ACL injury, but specific evidence of this as a causal factor has not been obtained to date. The biomechanical and epidemiologic literature on brace employment (prophylactic and functional) is equivocal and inconsistent.

In general, there is a need for studies addressing environmental risk factors that better integrate biomechanical and epidemiologic knowledge. Such studies would as well ideally consider the interaction of extrinsic and intrinsic factors (Griffin et al., 2006).

2.1.4.2 Anatomical risk factors

Several studies of ACL injury risk factors have focused on anatomical or anthropometric measures such as tibia length and thigh length (Uhorchak et al., 2003). The magnitude of the quadriceps femoris angle, the degree of static and dynamic knee valgus, foot pronation, body mass index (BMI), the width of the femoral notch, and ACL geometry are anatomical factors that have been associated with an increased risk for non-contact ACL injury (Griffin et al., 2006). Lower extremity bone lengths may underlie increased risk of ACL injuries ; however, anatomical measures often do not correlate with potential dynamic injury mechanisms (Myer et al., 2005a). Anatomical measures are difficult to modify by nature; therefore, the potential impact of research into these mechanisms is relatively small (Hewett et al., 2006).

The Q angle has been suggested as a contributing factor to the development of knee injuries by altering lower extremity kinematics (Heiderscheit et al., 2000, Mizuno et al., 2001). The Q-angle is formed between the vectors for the combined pull of the quadriceps femoris muscle and the patellar tendon (Hungerford and Barry, 1979). There is no strict conformity regarding standardised reference values, but Q-angles exceeding 15° in males and 20° in females are considered abnormal (Horton and Hall, 1989). There is a documented relationship between high Q-angle, patellar maltracking and anterior knee pain, and several authors have speculated that this sex-related anatomical difference may also lead to increased risk of ACL injury (Hutchinson and Ireland, 1995, Moeller and

Lamb, 1997). However, numerous studies have found no relationship between Q-angle and predisposition to ACL injury (Gray et al., 1985, Loudon et al., 1996). Not only is there no demonstrated link between ACL injury risk and Q-angle, but there is no consensus in the literature as regards Q-angle measurement approach (Lewis, 2000).

Women have a comparatively wider or differently shaped pelvis that could lead to an increased Q angle, and this increased angle could relate to increased injury risk (Zelisko et al., 1982, Agre and Baxter, 1987a). In contrast, Gray et al., (1985) have reported that injury rate differences were not related to anatomical differences such as Q angle. Statically determined Q angles do not appear to be predictive of either knee valgus or ACL injury risk during dynamic movement, thus supporting further exploration of other dynamic muscular and neuromuscular factors and their role in limb alignment during landing and cutting (Myer et al., 2005a, Gray et al., 1985).

The ACL is positioned in the femoral (intercondylar) notch, and a narrow notch could cause increased elongation of the ACL under high tension. Uhorchak et al., (2003) reported that women with a narrow intercondylar notch had a 16.8 times greater injury risk ratio than did those with a larger notch width. Shelbourne et al., (1998) stated that a small notch is associated with a small ACL and that sex is not the factor - it is just that more women than men have small notches. Other reports demonstrate no difference in notch width normalized to bone width in female and male athletes or an association between notch width and injury (Arendt and Dick, 1995, Hewett et al., 2005, Hutchinson and Ireland, 1995, LaPrade and Burnett, 1994). Several studies in the literature have reported no correlation between notch width and the incidence of non-contact ACL injuries but do not have sufficient power to make definitive conclusions (Griffin et al., 2006).

General joint laxity and hyperextension were found to significantly increase the risk for injury in female soccer players (Solomonow et al., 1987). Uhorchak et al., (2003) reported that women with generalised joint laxity had a 2.7 times larger risk of ACL injury than did those without laxity. Joint laxity influences not only sagittal knee motion (hyperextension) but also coronal knee motion (valgus), which can strain the ACL and be related to increased risk in female athletes (Boden et al., 2000, Hewett et al., 2005, Markolf et al., 1995, Markolf et al., 1978, Uhorchak et al., 2003). Increased hamstrings flexibility might be partially responsible for the decreased dynamic control of the knee in female athletes (Hewett et al., 1996, Huston and Wojtys, 1996). It shows that developmental differences in flexibility, especially hamstrings flexibility, might contribute to the post pubertal sex gap in knee injury rate; however, further research in this area is needed (Hewett et al., 2006).

Anatomical risk factors for ACL injury remain an intriguing and promising area of research. However, so far, conflicting data have resulted across a variety of study designs regarding the magnitude of the Q angle, the degree of static and dynamic knee valgus, the width of the femoral notch. Although discovering anatomical risk factors improves our understanding of the ACL injury risk, one must appreciate that if anatomical factors are found to be definitely associated with an increased risk of injury, they may be less modifiable than environmental, hormonal, muscular or neuromuscular factors (Griffin et al., 2006).

2.1.4.3 Hormonal risk factors

Estrogen levels are claimed to be associated with female ACL injury rates (Gray et al., 1985, Zelisko et al., 1982). Decreased ligament strength, as a result of cyclic changes in female hormones, might be a possible contributor to the higher incidence of female ACL injuries (Hewett et al., 2006). Increased attention to sex hormones as a risk factor for non-contact ACL injury followed Liu et al., (1996) of receptors for these hormones in ACL tissue obtained from male and female subjects. Because hormones are identified to affect ligament loading responses, and because of the higher incidence of ACL tears in women, a number of studies have been conducted to evaluate the role of sex hormones in ACL injury (Slauterbeck et al., 1999). Serum estrogen concentrations increase several-fold during the menstrual cycle (Samuel et al., 1996). Both estrogen and relaxin are known to affect the tensile properties of ligaments, and estrogen receptors are present in human ACL fibroblasts. Estradiol has been shown to decrease procollagen synthesis in cultured fibroblasts from a female ACL (Booth and Tipton, 1970, Liu et al., 1996, Samuel et al., 1996).

The association between the phase of the menstrual cycle and the incidence of non-contact ACL injury remains unclear (Griffin et al., 2006). Numerous studies have investigated the time of occurrence of non-contact ACL injury in females in relation to the phase of the menstrual cycle (Myklebust et al., 1997, Wojtys et al., 1998, Wojtys et al., 2002, Slauterbeck et al., 2002a); however, the findings are not in agreement. Some studies reported significantly higher incidence of ACL injury between days 10-14 (Wojtys et al., 1998, Wojtys et al., 2002) whereas others reported significantly higher incidence during days 1-2 of the menstrual cycle (Slauterbeck et al., 2002b). Also, days of significantly lower incidence of ACL injury have been reported between days l-9 (Wojtys et al., 2002) days 8-14 (Myklebust et al., 1997) and days 15-28 of the menstrual cycle (Wojtys et al., 2002). These results are consistent with previous studies that did not find alterations in torque produced about the knee joint at different points in the menstrual cycle (DiBrezzo et al., 1991, Friden et al., 2003, Janse de Jonge et al., 2001).

The isokinetic findings of Janse de Jonge et al., (2001) study agree well with studies by Gur (1997) and Lebrun et al., (1995), who also did not determine any changes over the menstrual cycle for maximal isokinetic knee flexion and extension strength. Both these studies proposed that menstrual cycle phase does not affect isokinetic knee flexion and extension strength, which is confirmed by the Janse de Jonge et al., (2001) study. In addition, the quadriceps strength properties, the electrically stimulated quadriceps fatigue and the isokinetic knee flexor and extensor fatigue did not change throughout the menstrual cycle (Janse de Jonge et al., 2001). At present, the influence of changes in hormone concentrations on the incidence of ACL injuries in females is not clear (Hughes and Watkins, 2006). Furthermore, general agreement has not been reached concerning the time in the menstrual cycle associated with increased injury incidence. Although the evidence is not definitive, the balance of evidence would indicate more injuries occur in early and late follicular phases. Future research should consider the inherent individual variability in cycle characteristics between women and accurately document each woman's hormone milieu by determining actual hormone concentrations (Griffin et al., 2006).

2.1.4.4 Neuromuscular risk factors

Research exploring neuromuscular risk factors continues to develop, and the risk factor elucidation is intertwined with a greater understanding of the mechanics of injury. Many controlled laboratory-based experimental studies have addressed neuromuscular risk factors. Although these studies give strong theoretical support to clinical observations, further studies are still needed to establish the association between the injury and proposed neuromuscular risk factors (Griffin et al., 2006). The proposed neuromuscular risk factors might be grouped as those related to altered movement patterns, altered activation patterns, and inadequate muscle stiffness.

Three neuromuscular deficits related to biomechanical or neuromuscular coordination include ligament dominance, quadriceps dominance, and leg dominance (Hewett et al., 2001). Andrews and Axe (1985) first introduced the concept of ligament dominance whereby the lower extremity musculature does not adequately absorb the forces during a sports manoeuvre resulting in excessive loading of the knee ligaments, especially the ACL, which resists anterior tibial translation and knee valgus. Ligament dominance frequently results in high ground reaction forces, valgus knee moments, and excessive knee valgus motion. Quadriceps dominance is an imbalance between the recruitment model of the knee flexors and extensors. Females have a tendency to rely on their quadriceps over their hamstrings to produce dynamic knee stability during jumping and landing activities (Huston and Wojtys, 1996). Leg dominance is an imbalance between muscular strength and recruitment patterns on opposite limbs, with one side often exhibiting greater dynamic control (Hewett et al., 1996, Knapik et al., 1991). Over-reliance on one limb places greater stress on that knee, where the weaker side might not effectively absorb the high forces associated with sporting activities.

Augmented ACL injury risk in female athletes is associated with the relatively low knee flexor to extensor ratio or hamstrings to quadriceps PT ratio (Hewett et al., 2006). Quadriceps contraction increases ACL strain in the first 30° to 45° of knee flexion, and isolated quadriceps contraction can create forces beyond those required for ACL tensile failure (Fleming et al., 2003, Lloyd, 2001, McNair et al., 1990, Myklebust et al., 1998).

Arms et al., (1984) confirmed that ACL strain increased to 45° of flexion and decreased at knee flexion angles greater than 60°. Beynnon et al., (1992) reported that the ACL was strained by quadriceps contraction at 30° but not at 90° using in vivo techniques. They also reported that quadriceps contraction significantly increased at 15° and 30° but decreased at 60° (Beynnon et al., 1995). Hewett et al., (2006) believed that co-activation of the hamstrings and quadriceps muscles may protect the knee joint not only against excessive anterior drawer, but also against knee abduction and dynamic lower extremity valgus. If the hamstrings are weak, quadriceps activation would have to be reduced to provide a net flexor moment required to perform the movement (Hewett et al., 2005, Hewett et al., 1996). Shortage in strength and activation of the hamstrings directly limit the potential for muscular co-contraction to protect ligaments (Solomonow et al., 1987). Co-contraction of the knee flexors is essential to balance active contraction of the quadriceps in order to compress the joint and assist in the control of high knee abduction torques and anterior tibial translation (Solomonow et al., 1987).

The augmented balance in strength and recruitment of the hamstring and gastrocnemius musculature relative to quadriceps may be a mechanism that protects the knee ligaments in male athletes. Sufficient co-contraction of the knee flexors may help balance active contraction of the quadriceps in order to compress the joint and assist in the control of high knee abduction torques or valgus collapse (Hewett et al., 2006). Suitable neuromuscular control may prevent the critical loading necessary to rupture the ACL during manoeuvers that place the athlete at risk for an injury. Female athletes, with reduced ability to adequately balance muscular recruitment through positions of high joint loading, may increase their risk of subsequent ligament failure (Hewett et al., 2005). During flexion exercises, female athletes display increased activation of their quadriceps relative to their hamstrings and increased anterior tibial loads during dynamic exercises (Markolf et al., 1995, Sell et al., 2004). Disproportional recruitment of the quadriceps musculature might lead to anterior shear force in female athletes. Thus, the available literature shows several potential altered hamstring activation strategies and suggests its potential to be related to increased risk of ACL injury.

In summary, environmental, anatomical, and hormonal, as well as a neuromuscular factors, have all been explored as possible risk factors for non-contact ACL injury. After reviewing the data on these risk factors, this literature here concurred with Meeuwisse's theory (1994), recently expanded by Krosshaug et al., (2005a) that non-contact ACL injuries arise from a complex interaction of multiple risk factors. Understanding the underlying causes or risk factors for one of the more severe sports-related knee injuries an ACL disruption is important for the development of intervention strategies and for identifying those at increased risk of injury. This provides a target group for intervention. The risk factors for ACL injury have been considered as either internal or external to an individual. However, the evidence regarding an athlete's complete external and internal risk factor profile for ACL injury is unclear because most of the investigations have studied isolated variables.

Although no definitive aetiology for the discrepancy in the occurrence of ACL injuries between the sexes has been established, structural, hormonal and neuromuscular factors have all been proposed (Hewett et al., 2007). Dynamic muscular control of knee joint alignment, specifically differences in muscle recruitment, firing patterns and strength may be partly responsible for the sex differences in the incidence of ACL injury. The proposed neuromuscular risk factors might be grouped as those related to altered movement patterns, altered activation patterns, and inadequate muscle stiffness. In the fatigued state, males and females use antagonist inhibition strategies by reducing hamstring activation (Pollard et al., 2006). The work of Padua et al., (2006) demonstrated greater co-activation ratios in females compared to males in a fatigued state and also suggest that adults move to an ankle dominant strategy (compared to knee strategy) to protect the knee on landing. Although these studies present some empirical support for clinical observations, further research is still needed to find the association between the injury and proposed neuromuscular risk factors in males and females, particularly with fatigue.

Most of the evidence suggesting a relationship between potential risk factors and injury incidence is based on indirect/retrospective evidence. This is especially relevant for the intrinsic risk factors and those that are both modifiable and non- modifiable. Importantly, the evidence of a relationship between neuromuscular performance capability, fatigue and injury incidence remains to be directly established. Potential muscular and neuromuscular imbalances may be related to components of the ACL injury mechanism in males and females. Hamstring recruitment has been shown to be significantly higher in men than in women. The hamstring to quadriceps peak torque ratio tends to be greater in men than in women which lead us to propose what any direct evidence that muscular and neuromuscular are important factors.

2.2 THE FUNCTIONAL DYNAMIC KNEE STABILITY

The ability of the knee joint to remain stable when subjected to the rapidly changing loads it withstands during activity is referred to as dynamic knee stability (Williams et al., 2001). Dynamic stability depends on the integration of articular geometry, soft tissue restraints, and the loads applied to the joint through weight bearing and muscle activation (Williams et al., 2001). Generally, several ligaments work synergistically to provide joint stability (Baratta et al., 1988). The anterior cruciate ligament (ACL) is an important stabilizer of the knee joint. This is due not only to the mechanical properties of the ligament but also to the afferent information provided to the central nervous system by the mechanoreceptors that exist in the ACL (Sjolander et al., 2002, Solomonow and Krogsgaard, 2001, Johansson et al., 1991a).

Dynamic knee stability is an important component required to reduce relative risk of injury, especially to the knee joint. There are numerous methods employed within the literature to try and measure/determine knee stability, include 3D kinematics using sophisticated camera systems, knee ligament arthrometers to directly determine joint laxity, restarted movement in some causes. Manual methods, knee joint position. The estimation of 3D human motion from a monocular sequence of 2D images is challenging for a variety of reasons. These include the non-linear dynamics of the limbs, ambiguities in the mapping from the 2D image to the 3D model, the similarity of the appearance of dierent limbs, self occlusions, kinematic singularities, and image noise. It is difficult to directly measure knee stability; however the eccentric ability of the hamstrings to co-contract to counter the torque produced by concentric quadriceps actions during knee extension is important in stabilising the knee (determined as the functional H/Q ratio [FH/Q]).In context of this thesis, term of dynamic knee stability refers to muscular and neuromuscular system that contributes to stability of the knee (see section 2.2.1)

The ACL is challenged by both intra-limb torques, generated by the muscles crossing the joint, internal torques, like a leg swing, and various external torques which are influenced by the velocity or direction of displacement, such as the translation of the centre of gravity of the body. Functional stability involves central processes and peripheral structures to maintain the integrity of the knee structures and limit the ACL strain during different phases of movement and physical activity (Moore et al., 2002). Athletic success depends on the ability to jump, run, and change direction at high speed in a rapidly changing environment. The knee joint is subjected to extremely high forces and moments during these activities because it lies between the two longest lever arms in the body and is surrounded by its most powerful muscles (Williams et al., 2001).

Muscle force-generating ability has been shown to be significantly higher in males than females (Kanehisa et al., 1996, Pincivero et al., 2000). However, there are few data comparing FH/Q ratio in males and females. The dynamic strength control ratio should give a appropriate measure relating to knee function. So, for minimising the injury risk, it has been proposed that attention should be paid to keeping the hamstring to quadriceps ratio close to unity (Agre and Baxter, 1987b). The hamstrings to quadricrps muscle strength ratio has been used as an indicator of normal balance between the knee flexors and extensors and it is a parameter commonly used to explain the muscle strength properties about the knee joint (Kannus, 1994, Baltzopoulos and Brodie, 1989).

The hamstring to quadriceps ratio has conventionally been expressed as concentric hamstrings to concentric quadriceps strength (Lund-Hanssen et al., 1996) which does not reflect the *functional* capacity of the knee during dynamic movement. Eccentric actions develop greater tension than concentric muscle actions performed at the same velocity, and are therefore considered more effective in providing muscle strength (Albert, 1995) and several studies have confirmed this claim (Cometti et al., 2001, Kannus, 1994, Ghena et al., 1991). Westing and Seger (1989) investigated the eccentric and concentric torque velocity characteristics of the quadriceps and hamstring muscle groups. They reported that mean concentric PT was significantly lower than the corresponding eccentric PT at all assessment velocities. Furtheremore, it was observed that mean eccentric torque did not change significantly with increasing eccentric velocity for either the quadriceps or hamstring muscles.

A FH/Q ratio of about 1.00 has been reported for fast isokinetic knee extension movement, indicating a significant capacity of the hamstring muscles to provide dynamic joint stabilisation during active knee extension (Aagaard et al., 1998). Knee joint stability is known to be important in risk of injury (Blackburn et al., 2009). The FH/Q ratio, outside the 0.7-1 range, when calculated near full knee extension (0º) suggests a potential increase in the relative risk of injury. A number of studies have now started to report the functional ratio but are mainly limited as they use peak torque (PT) which tends to occur in the mid-range of the movement rather than near full knee extension where injury is likely to occur. Studies also tend to use PT obtained from CON and ECC actions that do not occur at the same joint angle and therefore tells us little about co-contraction and is thus not functionally relevant. The FH/Q ratio is velocity and joint angle dependent (Aagard et al, 1998), and the functional ratio should be calculated at specified angles to avoid differences in PT between quadriceps and hamstrings due to varying joint angles. If it is to be accepted that injury occurrence is due to a specific hamstring weakness the FH/Q ratio should decrease when approaching full knee extension and with increasing angular velocity or in the presence of action-specific fatigue. Sex differences in functional ratio, taking into account joint angle and velocity, remain to be investigated, particularly in a fatigued state, which is surprising given the likely association of functional ratio with predisposition to injury (Croce et al., 1996).

2.2.1 The role of the hamstring and quadriceps muscles

The hamstrings are commonly referred to as ACL agonists and co-contract with the quadriceps during knee extension to counteract anterior tibial translation (Baratta et al., 1988, Aagaard et al., 2000). The hamstring muscles during leg extension assist the anterior cruciate ligament (ACL) in preventing anterior tibial drawer forces (More et al., 1993, Yasuda and Sasaki, 1987) by increasing joint stiffness, increasing the posterior pull and reducing anterior laxity force during quadriceps loading. This opposing force helps to decelerates the leg prior to full extension, preventing overextension and stabilises the knee joint throughout the range of motion (Baratta et al., 1988). The hamstrings therefore play an important part in maintaining knee joint stability (Coombs and Garbutt, 2002). Tensile strain on the ACL is significantly reduced when the hamstrings and the quadriceps co-activate during extension, compared to quadriceps activation alone (Yasuda and Sasaki, 1987, More et al., 1993, Draganich and Vahey, 1990). This reduction in ACL strain when the hamstrings sufficiently co-contract with the quadriceps is the basis for suggesting that a higher FH/Q ratio may reduce the relative risk of injury. Although there is no clear evidence of a link between FH/Q ratio and injury incidence, the data on ACL loading and co-contraction is compelling and propose a causal link between FH/Q ratio and injury incidence. further investigation is required to this causal link.

In the literature, it is well documented that the quadriceps muscle group possesses higher concentric mean torque values (20-40 % greater) than the hamstrings at all angular velocities (Goslin and Charteris, 1979, Wyatt and Edwards, 1981). Stafford and Grana,

(1984) tested the quadriceps and hamstring muscles of 60 intercollegiate soccer players across a range of angular velocities. They reported that the quadriceps possesses greater concentric torque than the hamstring muscles at all angular velocities, and the level of differences varied for different angular velocities (33% at 1.62, 28% at 3.24, and 20% at $300^{\circ}\cdot s^{-1}$). In addition, Agre and Baxter (1987) investigated the musculoskeletal profile of 25 male collegiate soccer players at $30^{\circ}\cdot s^{-1}$ and found a greater value (40%) in the quadriceps than in the hamstring in their participants. If the quadriceps torque greatly exceeds that of the hamstring, the ability to resist knee extension is reduced which may result in a forced stretch of the hamstrings and consequent muscle damage (Yasuda and Sasaki, 1987).

2.2.2 Proprioception and neuromuscular control in knee stability

Proprioception plays a main role in muscular control, the precision of motion and the stability in joints. The skin, muscles, tendons, menisci, capsule and ligaments, in and about the knee joint contain several receptors, which contribute to perception of movement and position (Boerboom et al., 2008). This control mechanism is essential as it helps to adjust muscle tension and therefore improve joint stability (Barrack et al., 1989, Hewett et al., 2002, Johansson et al., 1991b). Proprioception and neuromuscular control are two distinct mechanisms that complement each other in the processes of postural and joint stability. The sensorimotor system represents complex neurosensory and neuromuscular processes (Lephart et al., 2000). Proprioception is the afferent information arising from peripheral areas of the body that contribute to postural control, joint stability, and several sensations (Riemann and Lephart, 2002a). The perception and execution of musculoskeletal control and movement are mediated primarily by the central nervous system (CNS). The CNS receives input from 3 main subsystems: the somatosensory system; the vestibular system; and the visual system.

Neuromuscular control as explained by Riemann and Lephart (2002b) is the unconscious activation of dynamic stabilizers in preparation for and in response to joint loading and motion for the purpose of maintaining and restoring functional joint stability. Neuromuscular control is dependent on the accuracy of the afferent information received by the central nervous system. Therefore, it would be impossible to describe neuromuscular control of the knee without including the sensory aspect of the system.

Riemann and Lephart (2002a) consider two categories in which proprioceptive information in neuromuscular control can be separated. The first category involves the ability of the proprioceptors to alter motor programmes to adjust to unexpected perturbations in the external environment. The ability of the joint proprioceptors to take action to alterations in the external environment protects joints from injury. The second category is the role proprioception plays in the planning and modification of internally generated motor commands. Proprioception provides the information needed for neuromuscular control to keep the joints stable.

Alterations in the afferent input to the alpha motor neurons can potentially affect reactive muscular function and decrease the protection of the joints (Rizzu et al., 2000). Skinner et al., (1986) reported that during fatigue conditions subjects had significantly decreased proprioceptive abilities. They hypothesized that this was due to either altered afferent impulses from the muscles themselves or from abnormal stresses in the joint capsule as a result of the muscle fatigue (Skinner et al., 1986). Altered joint proprioception due to fatigue may impact on neuromuscular control (Rizzu et al., 2000). Because of the increased latency periods during the fatigued state, muscles may not be able to respond quickly enough to protect a joint from injury. Considering this time lapse and the need to develop sufficient muscle tension rapidly enough to provide dynamic knee stability, electromechanical delay (EMD) that described as the latency between the onset of electrical activity in a muscle and the onset of force generation by that muscle's contraction (Yavuz et al., 2010) should be considered when evaluating muscular responses to an imposed perturbation or injurious stress.

2.2.3 The role of co-activation and eccentric activity in knee joint function

The contribution of antagonists during particular phases of the movement is very important in many activities because the antagonists control and stabilize the joint when large forces are developed (Baratta et al., 1988, Patton and Mortensen, 1971, Kellis and Baltzopoulos, 1995). Co-activation of the hamstrings during active knee extension assists the ACL in maintaining knee joint stability by exerting an opposing force to anterior tibial translation (Baratta et al., 1988, Osternig et al., 1995). As a result, determination of the strength of the antagonists and its relationship to agonists has been extensively investigated (Kellis and Baltzopoulos, 1995). Electromyography (EMG) provides a direct and non-invasive indication of motor unit activity of the involved muscles during joint actions. The EMG technique has been used for the determination of the antagonistic activity during different joint movements (Hagood et al., 1990, Baratta et al., 1988, Solomonow et al., 1987).

Eccentric contractions occur when the load torque (i.e., resistance moment) forced on the muscle or a group of muscles is greater than the muscle torque produced by all activated motor units (Enoka, 1996). During an eccentric muscle action, the external mechanical load exerted on the solicited muscle triggers storage of elastic ‘recoil’ energy within the muscle-tendon system. During subsequent contraction, this stored energy is released to supplement the force produced by the solicited muscle fibres. As a result, the contraction requires a reduced metabolic energy cost for the same force production compared to standard concentric contractions (Abbott et al., 1952). Eccentric actions develop greater tension than concentric muscle actions performed at the same angle, and are considered to be more effective in improving muscle strength (Albert, 1995) as confirmed by several studies (Kannus, 1994, Ghena et al., 1991, Cometti et al., 2001). Westing and Seger (1989) investigated the eccentric and concentric torque-velocity characteristics. Quadriceps and hamstring strength of twenty participants were tested at angular velocities ranging from 1.08 to 6.48 rad.s^{-1}. They reported that mean concentric torque was significantly lower than the corresponding eccentric torque. They observed that mean eccentric torque did not change significantly with increasing eccentric velocity for either the quadriceps or hamstring muscles. At each test velocity, the concentric H/Q ratio was significantly lower than corresponding eccentric H/Q ratio.

It has been suggested that poor eccentric strength of the hamstring muscle group may cause hamstring strains (Stanton and Purdam, 1989). Worrell et al., (1991) did not find any differences in concentric or eccentric lower limb muscle torque between injured and uninjured athletes. Eccentric actions produce greater loading of the elastic component of skeletal muscle, which may help to impove sprinting and jumping performance, and may be useful in rehabilitation (Kellis and Baltzopoulos, 1995). If the risk of strains and tears is to be reduced, the ability of the muscle to resist forces should be improved (Bennett and Stauber, 1986). There are a number of factors to consider when examining the relationship between torque and movement velocity during eccentric actions. Most available studies have reported that maximal eccentric torque is not velocity-dependent (Kellis and Baltzopoulos, 1995). However, the nature of torque-velocity relationship seems to be associated with sex, age and even level of strength (Colliander and Tesch, 1989).

An insufficiency of hamstrings co-activation may lead to a lack of knee-joint stability, which can result in quadriceps muscle contractions creating unwanted stresses on internal joint structures, episodes of joint instability, and atrophy of the surrounding muscles (Solomonow et al., 1989). Although co-activation of the hamstring muscle during knee extension may seem counterproductive, it is thought that it provides joint stability and acts as a natural safety mechanism (Chan et al., 1996). The increase in antagonist activation acts as a braking mechanism which also reduces excessive tension on the anterior cruciate ligament (Tourny-Chollet and Leroy, 2002). The quadriceps is capable of generating much higher force than the hamstrings whilst both muscles are contracting concentrically suggesting that the hamstrings ability to stabilise the knee is limited. However, during functional movements the quadriceps are contracting concentrically whilst the hamstrings are contracting eccentrically (Chan et al., 1996). This would therefore indicate that the hamstrings are capable of providing sufficient joint stability during dynamic knee extension (Aagaard et al., 2000) in most situations.

The impact of the muscle action mode on the level of co-activation varies according to the different studies. The impact could be greater in plantar flexor muscles (Pinniger et al., 2000) compared with knee extensor muscles (Kellis and Baltzopoulos, 1998), whereas other studies show similar co-activation values regardless of neuromuscular solicitation type (Pousson et al., 1999, Amiridis et al., 1996).

During knee flexion exercises, females display increased co-activation of their quadriceps relative to their hamstrings which could increase anterior tibial loads during dynamic exercises. Other research groups have also suggested that disproportional recruitment of the vastus lateralis knee musculature results in increased anterior shear force in female athletes compared to their male counterparts (Markolf et al., 1995, Sell et al., 2004). Sell et al., (2004) reported that female athlete's exhibit a disproportionate (four times greater) firing of their lateral hamstrings, as assessed by EMG measurements, compared to males during the deceleration of a jump landing. Thus an unequal or low ratio of medial to lateral quadriceps recruitment may come together with increased lateral hamstring firing to compress the lateral joint, open the medial joint and increase anterior shear force.

2.3 THE HAMSTRING TO QUADRICEPS FUNCTIONAL RATIO

The torque ratio that has obtained the most attention in the literature is the hamstring to quadriceps (H:Q) torque ratio (Holcomb et al., 2007). If the torque of the quadriceps considerably exceed the torque of the hamstrings, subsequently both the hamstrings and anterior cruciate ligament (ACL) may become more susceptible to injury (Holcomb et al., 2007). However, with assistance from the hamstrings, the ACL stabilizes the knee by preventing anterior translation of the tibia on the femur (More et al., 1993, Kannus, 1988).

The hamstring-quadriceps ratio has until recently been based on the concentric torque of these two muscle groups (Coombs and Garbutt, 2002). However, co-activation of these muscle groups is identified to occur and takes place through opposing muscle action modes. Through leg extension the quadriceps produce a concentric action (Qcon) and the hamstrings produce an eccentric action (Hecc). On the other hand, the hamstrings contract concentrically (Hcon) and the quadriceps eccentrically (Qecc) during leg flexion. Consequently, in order to accurately assess the balancing nature of the hamstrings about the knee joint, the hamstring-quadriceps ratio should be explained either as a Hecc/Qcon ratio representing knee extension, or a Hcon/Qecc ratio representing knee flexion (Coombs and Garbutt, 2002). A recent study on adults clearly links the relative risk of injury to muscle imbalance of the FH/Q ratio (Yeung et al., 2009).

The H/Q ratio has conventionally been determined as maximal knee flexion torque divided by maximal knee extension torque obtained at a given knee angular velocity and contraction mode (isometric, concentric, eccentric). For example, the conventional concentric H/Q torque ratio is estimated by dividing maximal concentric knee flexor (hamstring) moment by the maximal concentric knee extensor (quadriceps) moment obtained at a given angular velocity. However, since opposing muscles are not capable of simultaneous concentric muscle actions, the value of the conventional ratio has been questioned (Croisier et al., 2002). The conventional ratio which lack functional relevance has been examined by numerous authors. In fact, during knee extension, antagonistic eccentric, not concentric, hamstrings co-activation decreases the anterior shear forces induced by the concentric quadriceps muscle group action (Senter and Hame, 2006).

The functional ratio, which compares concentric muscle actions to eccentric muscle actions of the opposing muscles, evaluates actions that do occur simultaneously and are more functional (Aagaard et al., 1998, Aagaard et al., 1995, Hole et al., 2000). Therefore, it has recently been proposed that the agonist-antagonist torque relationship for knee extension may be better described by a FH/Q ratio of eccentric hamstring to concentric quadriceps muscle torque. Therefore, accurate determinations of concentric and eccentric torque production are required to assess the FH/Q ratio. A high level of quadriceps torque compared to hamstring torque will reduce the H/Q ratio and a ratio of less than 55% may represent a quadriceps dominant athlete. Subsequently this may mean that hamstring recruitment patterns are less than optimal during dynamic tasks.

2.3.1 Assessment of isokinetic torque

The most useful measure of muscles performance is the moment of rotational force or torque, since most of human movement occurs by rotation of a series of bodily segments and even in complicated joints there is always an axis about which the moment is occurring (Aagaard et al., 1996). The main advantage of isokinetic dynamometry is that it accounts for the differences in mechanical advantage across joint angles and angular velocities and offers maximal loading throughout the range of movement unlike isometric or isotonic assessment (Warren et al., 1999). If isokinetic measures are to be used as a valid indicator of dynamic muscle characteristics they need to be valid and reliable (Warren et al., 1999). Isokinetic dynamometry is a tool commonly used to measure torque at various joints. Contemporary isokinetic devices allow the quantification of a number of specific functional variables including peak torque, work and power. Peak torque, referring to the single highest torque output produced by a muscle action as the limb moves through a range of motion is the most commonly used isokinetic variable (Kannus, 1994).

The primary advantage of isokinetic resistance is that a muscle group may be exercised to its maximum potential throughout the knee joint's entire range of available motion. Isokinetic exercise may be used to quantify the quadriceps and hamstring muscle groups' abilities to generate torque or force and is also useful as an exercise modality in the restoration of either muscle group's pre-injury level of strength. A muscle has only the capacity to generate tension or to relax. If the force produced by a muscle is measured about a joint's axis of rotation, the moment of force is known as torque. Torque may be measured as a peak value from the highest point of a given torque curve or at specific angle, or it may be expressed as an average value from each point along the entire curve. If the force and distance of a given muscle contraction are known, the tension produced by a muscle is expressed as work. If the quantity of time required to produce work is known, the ability of the muscle to generate power may be determined. Some clinicians believe that assessment of torque at slow isokinetic test velocities reflects "strength," while the torque produced at high test velocities represents "power." However, torque, power, and work may be assessed at slow, intermediate, or fast isokinetic test velocities.

Modern isokinetic dynamometers such as the Biodex System 3 offer an ECC/ECC mode that may facilitate easier performance across a range of low to high knee angular velocities. This mode requires participants only to concentrate on resisting the lever instead of thinking about two different types of muscle action which have different control mechanisms by the nervous system (Enoka, 1996). During concentric assessments participants are required to attempt to accelerate the limb, applying maximum force against the lever arm. For assessment of eccentric torque, participants are required to resist the external force applied by the dynamometer as it moves the limb through the range of motion. It has been suggested (Kellis and Baltzopoulos, 1998) that the activities in which the individual participates should be examined, rather than isolated CON or ECC conditions, reflecting the natural movement patterns of dynamic alternating sequences of ECC and CON work.

Muscle fibres contain fibrils which in turn comprise of actin and myosin. These filaments are interlaced with one another and are joined by cross bridges where tension is created and the muscle is caused to shorten or lengthen. The muscle and cross bridge interactions are considered to be the contractile element, as they cause shortening and lengthening of the muscle (Winter, 1991). One important consideration when measuring torque production is hip joint position as this will influence the length tension relationship. In addition, the importance of the eccentric action of the hamstrings includes the promotion of hip stabilisation to stabalise the hip flexor moment, which in turn neutralizes the tendency of the quadriceps to cause anterior translation of the tibia on the femur. A number of previous studies have examined the influence of hip position on knee torque (Black et al., 1993, Worrell et al., 1990). Isokinetic assessments of the knee joint muscles can be performed in a prone, supine or sitting position. Torque values appear to be significantly greater for knee flexion in a sitting position when compared to supine (Black et al., 1993). Assessments in the prone and supine position provide closer approximation of the length tension relationship of the hamstring and quadriceps muscles during many functional and sporting activities (Worrell et al., 1990).

Isokinetic dynamometry is currently advocated as the best method for testing muscular strength as it provides an objective assessment and an accurate quantification of torque (Urquhart et al., 1995). The major advantage of isokinetic assessment is that the maximal muscular force that can be applied over a range of movement can be measured under dynamic conditions, provided that the pre-set velocity has been attained by the moving limb (Baltzopoulos and Brodie, 1989). The angular velocity refers to the velocity of the lever arm and limb segment and not to the linear shortening or lengthening velocity of the muscles involved. The torque-velocity relationship illustrates the ability of muscle to produce torque depending on the angular velocity (Yeadon et al., 2006). The torque produced by a muscle shortening at a high velocity will always be less than at a slow velocity except in eccentric action where torque increases or plateaus with velocity (Elftman, 1966).

There are very different characteristics and control mechanisms of these two actions, therefore the assessment of both types of action (Con/Ecc) are essential for a complete understanding of torque potential. The low functional Hcon/Qecc ratio values for fast isokinetic knee flexion observed (0.3 to 0.4) in the study of Aagaard et al., (1998) correspond well to findings of previous studies (Aagaard et al., 1995, Aagaard et al., 1996). These findings perhaps suggest that the hamstring muscles may have a reduced capacity for dynamic knee joint stabilisation in active knee flexion movements that involve eccentric quadriceps muscle action. In regulating limb velocity, the dynamometer exerts an opposing torque against the accelerating limb, often resulting in a transient peak in the torque curve, (Sapega et al., 1982).

Isokinetic dynamometers offer automated procedures for the correction of the effects of gravity. The gravitational torque of the limb-lever arm is automatically added to torque measurement of the muscles opposed by gravity and subtracted from the torque of the muscle facilitated by the force of gravity. Regardless of the muscle group, acceleration of the limb and resistance to acceleration, due to gravity, will inflate hamstring to quadriceps ratio, confounding the determination of these ratios. Early work by Winter et al., (1981) found that when gravitational torque are not taken into account knee extension may be underestimated by 26 to 43% and knee flexion by as much as 55 to 510%. In turn the percentage error is large for less forceful actions and decreases as the force of the muscle action increases. This is due to the fact that because gravitational torque remains constant for the same testing condition the size of the error is dependent on the magnitude of the muscular force (Baltzopoulos and Brodie, 1989).

2.3.2 Reliability studies of isokinetic torque

Fundamental to valid interpretation of isokinetic test data is the reliability of measurement. Reproducibility indicates the extent to which the instrument yields the same measurements on repeated episodes by either the same tester or different testers (Kaminski et al., 1995). Factors that might positively or negatively affect the reliability of isokinetic torque measurements include participant motivation, positioning, stabilisation, biological variation and consistency of adherence to the test protocol and pre-test instructions (Sapega, 1990, Rothstein, 1985). It is essential that the clinician or researcher understand that published reliability reports are typically specific to the procedures used and described in each study. Rothstein (1985) reinforces that reliability is specific to the procedure used and should not be generalised to other machines, joints, muscle actions, velocities, or protocols.

To improve reliability, in repeated measurements, it is central to record the dynamometer adjustments and apply them consistently from one session to the next (Burdett and Vanswearingen, 1987). The reliability of the measurements equally depends on the reproducibility of the machinery which is assessed by the tester. The dynamometer head has to be adequately calibrated and the tester able to thoroughly align the centre of rotation of the knee joint and the centre of the dynamometer head. Ideally repeated torque measurements should be made at constant joint angles and with well defined angular velocity parameters (Warren et al., 1999). Raw data analysis is an important to consider in relation to reliability since it has been demonstrated that isokinetic dynamometers are not truly isokinetic and that the lever goes through three phases: acceleration, constant velocity and deceleration.

Isokinetic tests to determine torque in adults display high reliability, depending on the protocol and joint used (Kellis and Baltzopoulos, 1995) but in general reliability appears higher in CON actions. Coefficients for flexion PT ranged from 0.92 at 2.08 rad·s^{-1} to 0.95 at 4.2 rad·s^{-1} (Brown et al., 1993). Pincevero et al., (1997) also utilised the Biodex System-2 to determine the reliability on 2 occasions separated by 7 days of CON PT measurements in adults. Intraclass correlation co-efficients (ICCs) of 0.96 to 0.97 were obtained for PT at 1.04 and 3.14 rad·s^{-1} demonstrating, in agreement with Brown et al., (1993) that the Biodex System 2 dynamometer measures highly reliable CON PT in adults. Kaminski and Dover (2001) have also determined that concentric inversion and reversion peak- and average-torque values derived from the Biodex System 3 isokinetic dynamometer on 2 occasions, with a minimum of 7 days between sessions in a group of healthy young men and women, Right-reversion PT ICC measures were 0,54 and 0,68 for 30°·s^{-1} and 120°·s^{-1}, respectively Left-reversion PT ICC values were 0,76 and 0,77 for 30°·s^{-1} and 120°·s^{-1}, respectively. The PT ICC value calculated for right inversion at 30°·s^{-1} was 0,87, and at 120°·s^{-1} the ICC was 0,92.

The reliability of eccentric PT has been investigated by a number of authors (Steiner et al., 1993, Tredinnick and Duncan, 1988, Wilhite et al., 1992). Steiner et al., (1993) reported that knee flexion average torque measurements were more reliable than extension PT at both 1.04 and 3.14 rad·s^{-1}. ICCs of 0.88 at 1.04 rad·s^{-1} and 0.88 at 3.14 rad·s^{-1} were obtained for knee extension average torque, and for knee flexion average torque the ICCs were 0.91 and 0.96 at the two velocities respectively. This reflects good reliability of isokinetic ECC knee flexion average torque as measured on the Lido Linea closed kinetic chain isokinetic dynamometer. A factor that appears to influence the reliability of ECC measurements more so than CON is the familiarity of the participants with ECC actions. Steiner et al. (1993) reported considerable variation in participant's ability to maintain ECC moment through the total range of motion (ROM), especially at high angular velocities. This could be partly attributed to the fact that they included a same-session familiarisation instead of a familiarisation on a day prior to the first test. This inability of adult participants to maintain ECC torque throughout the range of motion could have resulted in the low reliability (ICC=0.47) of average ECC torque measurement at 1.04 rad·s^{-1} as demonstrated by Tredinnick and Duncan (1988). Most commercially available dynamometers require the participant to produce a preset torque load during isokinetic ECC testing throughout the range of the movement. If the participant fails to produce this preload throughout the movement the lever arm will stall producing discomfort for the participant. Newer dynamometers, such as the one used in the present thesis is Biodex System 3 which have a passive eccentric mode where the lever can move throughout the range of motion irrespective of ECC torque produced by the participant. This mode is particularly useful when testing ECC torque during faster velocity movements, as the constant velocity period is usually short and any stalling of the lever arm by not meeting the ECC preload will reduce the constant velocity period.

When comparing reliability of ECC and CON torque determination, previous studies have shown that peak CON torque testing in 9/10 year old boys is more reliable than ECC torque testing (Deighan et al., 2003). Deighan et al., (2003) found that, at 0.51 rad·s^{-1}, hamstrings ECC PT assessment (ICC = 0.63) was less reliable than quadriceps CON assessment (ICC = 0.76). The findings of excellent reliability (ICC $\geq$ 0.90) for the force output with maximal voluntary isometric activations (MVIA) is consistent with the literature for prone extension postures (Plamondon et al., 1999), as well as for standing (Rytokoski, 1994) and seated dynamometry (Robinson et al., 1991, Smidt et al., 1983). Interestingly, there are no other studies making this comparison between the reliability of ECC and CON torque determination.

Making generalisations about reliability for adult groups, tested on different dynamometers, with various protocols, is to be approached with caution (Perrin, 1993). This is reiterated by Ellenbecker and Roetert, (1995) who stated that caution must be exhibited when comparing data between isokinetic dynamometers related to significant differences in both relative and absolute torque quantification. In addition Gleeson and Mercer, (1996) and Kellis, (1996) stated that measurment of flexion is more varible and less reliable than measures of extension. Additionally, the observed significant time-of-day effect suggests that appropriate comparison of maximal isokinetic leg strength can only be achieved based on data obtained within 30 min of the same time of day (Wyse et al., 1994). Brown et al., (1993) found a decrease in reliability with increasing velocity, and Johnson and Siegel, (1978) demonstrated less measurement error at slower limb movement velocity. This is further supported by Kellis, (1996) who indicated, by testing over five velocities (0.52 rad.s^{-1} to 3.14 rad.s^{-1}), that moments recorded at slower angular velocities are more reliable. Kellis (1996) concluded that eccentric and concentric knee extension and flexion reliability is high but are infuenced by the angular velocity used.

An habituation period is critical for strength testing as this essential period of learning facilitates a phase in which the specific movements, neuromuscular patterns and demands of the test become familiar to the individual. Previous study (Deighan et al., 2003) have reported good reliability in repeated isokinetic actions of the knee (extension r = 0.95; flexion r = 0.85); isokinetic actions of the elbow (extension r = 0. 97; flexion r = 0.87) and isometric hand grip data (r = 0.92) this study also have reported limits of agreement showing no systematic difference in knee and elbow peak torque measured on two separate occasions. Gleeson and Mercer, (1996) suggested that intra-day reliability is very good (coefficient of variation: 4.0 – 8.8%) but this may mask the reality, by underestimating the true biological variability inherent in isokinetic leg torque test performance. A recent study on prepubertal soccer players has reported systematic bias in concentric and eccentric knee torque, although these improvements, 3 to 7 %, were relatively small (Iga et al., 2006). It would appear that strength testing, irrespective of muscle action or muscle joint assessed, has a test-retest variation of around 4-9 %. Therefore, they suggested that all reliability studies should test - retest over a range of days and not only within the same day. It is imperative that both clinicians and researchers be cognizant of the potential sources of error that might influence the reliability of the isokinetic measurements and use standardized protocols and recommended techniques for performing isokinetic assessments to minimize the errors.

Interclass correlation coefficients for trial reliability and day-to-day reliability were reported in the study of Drouin et al., (2004) and observations demonstrated that the Biodex System 3 isokinetic dynamometer was a mechanically reliable instrument (ICC 0.99-1.00) for the valid measurement of angular position, isometric concentric at slow to moderately high velocities ($<300°\cdot s^{-1}$). Within the limitations of Drouin et al., (2004) study, the Biodex System 3 isokinetic dynamometer provided mechanically reliable measures of torque, position and velocity on repeated trials performed on the same day as well as on different days. Concentric measures were reliable up to approximately 4.2 $rad \cdot s^{-1}$, with a systematic decrease in reliability occurring at higher test velocities (Drouin et al., 2004). Isokinetic testing has shown acceptable average torque reliability for knee extensions between trials and days for both concentric and eccentric actions (Drouin et al., 2004), and for elbow extensors, trunk extensors and trunk flexors at different isokinetic velocities (Madsen, 1996). Gleeson and Mercer, (1996) work has surmised that there is good agreement in outcomes of day to day testing of adults using isokinetic dynamometry.

To decrease intra-participant variation and improve the reliability of isokinetic testing, practical guidelines should be followed (Sorensen et al., 1998). The dynamometer is novel to most participants so several practice trials may be required in order to achieve reliable torque reading. It is recommended that participants perform as many repetitions as needed to understand what is required during the testing or training protocol. In active young individuals, a single session has been reported as enough habituation to sufficiently increase reliability (Sorensen et al., 1998). Instructions should be concise, parsimonious and consistent between tests, and verbal commands should be explicit as to every facet of the procedure. Those include where to grasp, how to breathe, what to do with the contra lateral limb, how to push or pull in both directions, how to give a maximal effort, what constitutes one full repetition and how many repetitions to perform (Brown and Weir, 2001).

2.3.3 The force-velocity relationship

The effect of velocity of muscle shortening or lengthening on force output has been examined extensively since the pioneering work of Hill (1938). The ability of a muscle to generate concentric force is greatest at slow isokinetic velocities and decreases non-linearly as the test velocity increases. These effects are described by the classical force-velocity relationship described by Hill (1938) and others. The early study of Barnes (1980) indicated that both torque and motor-unit electrical activity decreased as contractile velocity increased and the relationship between torque and integrated electromyographic activity was linear and highly significant. Therefore, the decline in torque output due to increasing angular velocity is a result of different activation of motor units at different velocities.

Force-velocity relationship has been confirmed in isokinetic assessments of soccer players. Costain and Williams, (1984) measured the quadricep and hamstring torque levels of 16 high school soccer players using a Cybex II dynamometer at a slow (0.54 rad.s^{-1}) and fast (3.24 rad.s^{-1}) velocity. They reported a significant decrease in CON PT in both muscle groups from the slow to the fast velocity. In addition, Stafford and Grana, (1984) assessed knee extensors and flexors of 60 intercollegiate soccer players at functional angular velocities of 1.62, 3.24 and 5.4 rad.s^{-1} on the Cybex II and found the same results.

According to Westing et al., (1990) the theory that a tension reducing mechanism can become active during maximum ECC efforts ‘appears to be theoretically sound because of the risk of damage during extremely forceful contractions’ (p. 22). Westing et al., (1991) have measured EMG amplitude and average torque of the knee extensors in 14 highly trained adult males. They found that EMG activity was significantly lower under ECC loading than velocity matched CON loading, suggesting that even in highly trained adult males under high tension conditions (ECC actions), the neural drive was reduced despite maximal voluntary effort. They also concluded that this may protect the musculoskeletal system from an injury that could result from full muscle activation. A reduced neural drive during maximal CON and well as ECC actions has recently been demonstrated using the interpolated twitch technique (ITT) (Babault et al., 2001). Also, the studies by Westing et al., (1990) used participants that were 'highly trained' and could perhaps activate the knee extensors fully during CON actions because of this. Most studies have assessed isokinetic torque with CON muscle actions but it cannot be assumed that the results of these studies can be applied to ECC actions which have unique muscle mechanics and neural control mechanisms.

As dictated by the force-velocity relationship the FH/Q ratio has been shown to increase as angular velocity increases in pubertal children, teenagers and adults for both sexes (De Ste Croix et al., 2007, Kellis and Katis, 2007). The flattening of the ECC force-velocity curve has been demonstrated by other authors in knee extensors and flexors of adult men and women (Westing and Seger, 1989; Westing et al., 1990), but others have reported that ECC force increases with increasing velocity (Colliander and Tesch, 1989). However, as dictated by the force-velocity relationship, the ratio of ECC to CON force or torque (ECC/CON ratio) should increase as angular velocity increases (Colliander and Tesch, 1989; Griffin et al., 1993). The fact that studies have employed various movement velocities, often without providing any explanation for the choice, limits the ability to compare results across studies. Future research should include the identification of optimal test velocities for populations

2.3.4 The effect of angular velocity and joint angle on H/Q ratio

There are few studies that have examined the sex differences in factors that may be associated with dynamic knee stability and relative risk of injury. This is somewhat surprising given the epidemiological data indicating that females appear to be the most 'at-risk' group for non-contact ACL injury (Hewett et al., 2005). Coplin, (1971) stated that an imbalance in torque between the knee extensors and knee flexors muscle groups is a factor which leads to an increase in the susceptibility to joint as well as muscle injury. Fowler and Reilly, (1993) reported that the ratio between the torque of the knee extensors and knee flexors is of particular interest, with a low ratio being associated with an increased risk of injury. The muscle groups on both sides of a joint act reciprocally to produce smooth and coordinated motion. When a muscle group generates a desired joint action it is the agonist creating the observed motion. The muscle group producing the opposite joint action is the antagonist (Perrin, 1993). The reciprocal muscle group ratio has been thought to be an indicator of muscular balance or imbalance around the joint (Baltzopoulos and Brodie, 1989).

Research findings highlight the importance of joint angle, angular velocity and action-specificity when calculating the FH/Q ratio. It has been found that ACL rupture is most likely to occur near full knee extension during high velocity movement (Renstrom et al., 2008). If it is to be accepted that a low FH/Q ratio may increase the relative risk of injury then it is essential to determine whether the ratio is reduced when: a) approaching full knee extension b) with increasing angular velocity c) in the presence of action-specific fatigue. The inability of the hamstrings to absorb the anterior tibial forces induced by the concentric quadriceps action under such conditions is clearly of great interest. However, Aagaard et al., (1995) calculated the FH/Q ratio based on isokinetic PTand torque at varying degrees of knee flexion at angular velocities 30, 120 and 240°/s^{-1} and they found that the FH/Q ratio increased with decreased joint angle and increasing angular velocity. The antagonist muscle group function is angle specific since it has to provide adequate anti-shear stabilising torque at the same joint angle as the concentric action of the agonist muscle group.

The joint angle specific FH/Q ratio has been briefly considered (Aagaard et al., 1998) but has remained largely ignored in the literature, despite being a potentially confounding variable when describing functional deficiencies. The calculation of the FH/Q ratio should be joint angle and angular velocity specific since hamstrings eccentric PT and quadriceps concentric PT do not occur at the same joint angle, and the angular specificities of the FH/Q ratio remain to be elucidated especially near full knee extension and after fatigue. Near full knee extension, static stability is reduced and functional stability relies mainly on dynamic stability to protect the knee structures (Griffin et al., 2006). However, this remains to be investigated, especially in females, and using appropriate fatiguing protocols.

Few studies appear to have examined angle specific FH/Q ratios across a range of velocities and in both sexes. Aagaard et al., (1998) have used female and male track athletes to investigate joint angle-specific FH/Q ratio and reported an increase in the FH/Q ratio with decreased joint angle at 50 degrees of extension. However, they ignored joint angles lower than 30 degrees, where dynamic stability is often challenged. Coombs and Garbutt, (2002) used a small sample of 9 female and 6 male recreational athletes to calculate joint angle-specific FH/Q ratio values throughout 90 degrees range of movement and found increasing FH/Q ratio as the joint moves closer to full extension, with the greatest FH/Q ratio found at 0.17 rad. Kellis and Katis, (2007) reported that the Hecc/Qcon ratio of males significantly increased as the knee extended at increased angular velocity reaching a value of 3.14 ± 1.95 at near full extension. This would appear to suggest that adults for both sexes compensate for known reduced stability of the joint which may reduce injury risk near full knee extension.

The recent work of Forbes et al., (2009) highlights this issue further where angles of PT for concentric quadriceps ranged from 72 - 78º in 12 to 18 year-olds compared with eccentric hamstring angles of PT which ranged from 31-38º. Therefore within current literature torques achieved at different angles are being used to represent a ratio which should be describing the ability of opposing torques to counteract each other (e.g., at the same joint angle). This ambiguity clearly does not help in elucidating the functional role that these muscles play in stabilizing the knee. Furthermore, the joint angle where non-contact ACL injury is mostly likely to occur is not at the point where PT is generated. Peak concentric and eccentric torque production is likely to occur in the mid-late range of the movement (around 30-80º of knee flexion), whereas it is well recognised that injury is likely to occur when the knee is closer to full extension (0-30º of knee flexion). Based on this knowledge it would seem more appropriate to calculate the FH/Q ratio using angle specific torque values close to full extension. It is clear that more data are required on the FH/Q ratio, especially using angle specific data and in females. Whether this will change our understanding of, and sex associated changes in, dynamic knee stability and the susceptibility to knee injury remains to be established.

A recent study by De Ste Croix et al., (2007) reported a significant velocity effect on FH/Q ratio in prepubertal children, teenagers and adults for both sexes. The FH/Q ratio was significantly higher at 3.14 rad.s^{-1} (1.12) compared to 0.52 rad.s^{-1} (0.8). This increase in the ratio at higher velocities provides some protection against the significant anterior tibial translation or shear at high quadriceps forces, and increase in internal rotation of the tibia in relation to the femur (Gerodimos et al., 2003). Irrespective of age or sex, the increase in co-activation of the hamstrings during high velocity movements significantly contributes to counterbalance this tibial shear or rotation. This data reinforces that the FH/Q ratio is a more relevant estimate of the capacity for muscular knee joint stabilisation than conventional ratios. It is important therefore that when making age and sex associated comparisons of the FH/Q ratio movement velocity are taken into account.

Maximum voluntary joint torque changes substantially with joint angle and angular velocity, due in part to the muscle force–length (Sale et al., 1982) and force–velocity (Westing et al., 1990) relationship. Accounting for strength variations with joint angle and angular velocity could lead to a better understanding of the role of agonist and antagonist muscle groups in human movements. Irrespective of sex the increase in co-activation of the hamstrings during high velocity movements significantly contributes to counterbalance the tibial shear or rotation. These findings suggest that the FH/Q ratio is a more relevant estimate of the capacity for muscular knee joint stabilisation than conventional ratios, particularly when joint angle and angular velocity are specified. It is important therefore, that when making sex associated comparisons of the FH/Q ratio, movement velocity and joint angle are taken into account.

2.3.5 Sex differences in FH/Q ratio

Consistent with data from the National Collegiate Athletic Association Injury Surveillance System, knee injuries have increased among female basketball and soccer players compared with their male counterparts (Powell and Barber-Foss, 2000, Arendt and Dick, 1995). The proposed greater prevalence of muscle imbalances among female than male athletes suggests that the hamstring-to-quadriceps (H/Q) ratio may be a mitigating factor for anterior cruciate ligament tears (Moeller and Lamb, 1997, Hewett et al., 1999, Huston and Wojtys, 1996). Also, Devan et al., (2004) have found that H/Q ratio below normal range at 300°·s^{-1} was associated with an increased prevalence of overuse knee injuries among female collegiate athletes.

Some authors have suggested that the sex difference in the FH/Q ratio is due to a lower capacity for CON rather than a higher capacity for ECC force production in females (Seger and Thorstensson, 2000). There is contrary evidence, however, in the form of a superior ability of females compared to males in utilising stored elastic energy in the muscle-tendon unit (Komi and Bosco, 1978). A high level of quadriceps strength compared to hamstring strength will reduce the FH/Q ratio and a ratio of less than 55% may represent a quadriceps dominant athlete. It has been suggested that the predisposition to greater relative risk in females is due to the fact that they may be predominantly quadriceps dominant, especially in athletic populations. Data to suggest this is conflicting as some studies have found no significant differences between males and females in the FH/Q ratio, whereas (Kong and Burns, 2010, Bojsen-Moller et al., 2007) others have reported a higher FH/Q ratio in males compared with females (Calmels et al., 1997, Yoon et al., 1991). These conflicting findings regarding the effect of sex on FH/Q ratio may be related to the different age ranges and training background of participants. Moreover, it has been suggested that sex differences in isokinetic FH:Q ratios are generally observed only at high knee angular velocities that approach those during sports activities (Hewett et al., 2008). Thus the range of velocities employed in the above studies may have influenced whether sex differences were identified or not. In an applied sense, these data suggest that stabilisation of the knee joint during high movements velocity, with high eccentric knee extension torque, is less optimal in females compared to males.

More data are required to reinforce whether or not there are sex differences in the FH/Q ratio. However, based on very limited data concerning sex differences in FH/Q ratio we might speculate that sex differences in the relative risk of non-contact ACL injury may additionally be attributed to factors other than those that are purely muscular in nature. For example, neuromuscular recruitment may play a crucial role in the sex difference related to relative risk of injury. It has been suggested that sex differences in adults in the FH/Q ratio of the knee joint are due to differences in percentage motor unit activation (%MUA) during maximal voluntary actions, with women having a lower %MUA than men during CON actions (Westing and Seger, 1989), but not ECC actions, possibly related to the separate neural control mechanisms for the respective muscle actions (Enoka, 1996).

Fatigue may affect men and women differently. Pincivero et al., (2003) reported that men exhibited higher knee flexion and extension torques, as well as, greater work and power production when compared to women. However, it was reported that the men fatigued quicker during maximal effort muscle contractions and during sub-maximal contractions men and women fatigue at the same rates but men still exhibited greater torque productions during knee extension (Pincivero et al., 2003). The higher rate of muscle fatigue demonstrated by males during voluntary, maximal effort quadriceps femoris contractions may also be affected by the method of quantification. Specifically, males were observed to produce significantly greater knee extensor and flexor peak torque, work, and power than females when corrected for body mass; not surprisingly, the males exhibited a greater rate of muscle fatigue than the females. However, it is clear that numerous factors may play a significant role in the sex-specific muscle fatigue. To date, evidence demonstrates that males possess an inherent ability to generate higher levels of torque than females, and that females appear to experience muscle fatigue at a slower rate. This will be discussed in greater detail in fatigue section (2.5).

2.4 ELECTROMYOGRAPHY (EMG)

Electromyography (EMG) refers to the study of the electrical signals originating from the muscle (Basmajian and De Luca, 1985). Muscles produce electrical activity during the course of each muscle action. The major aim of using EMG is to analyse the function and co-ordination of muscle under different movements (Jonsson, 1978). Surface electromyography (sEMG) is a tool that measures the electrical activity of a muscle or muscle group as it lengthens or shortens and does work (Cram et al., 1998). It is not a measure of muscle force but it can measure muscle timing (onset and offset) and amplitude which can provide information about the neuromuscular control mechanisms of the body (Cram et al., 1998).

The voltage output detected from the muscle by EMG systems is the result of the depolarisation and repolarisation of the surface membrane of the muscle fibre causing action potentials. The number of muscle fibres in a motor unit varies depending on the level of control required by that muscle. Muscles that produce fine movements (i.e., fingers, eyes) have a small number of muscle fibres per motor unit (~300 fibres per unit), whereas large muscles in the leg (that are used primarily for gross movements) comprise a large number of muscle fibres per motor unit (~2000 fibres per unit) (Jones et al., 2004).

Considering the role of the musculature in maintaining joint equilibrium and stability at the knee, there has been considerable interest in investigating neuromuscular response characteristics and their association with ACL injury. A number of research models have employed sEMG to evaluate activation patterns at the knee after joint loading or perturbation (Baratta et al., 1988, Gauffin and Tropp, 1992, Huston and Wojtys, 1996, McNair and Marshall, 1994, Smith et al., 1993). However, most of these models have evaluated this relationship from a post injury, rehabilitative reference point rather than a pre injury, predictive one.

Time to PT has been used as a surrogate for neuromuscular activation. However, time to PT is not a true measure of EMD; rather, true EMD can be measured if EMG data are collected simultaneously with an isokinetic dynamometer or other force transducer and if the precise time at which force is initiated (rather than peaked) is determined (Shultz and Perrin, 1999).

2.4.1 EMG assessment of muscle function

Scientists working in the sports or occupational environment prefer to use surface electrodes instead of indwelling electrodes (Clarys, 2000), as indwelling electrodes are considered to be invasive (Clarys and Cabri, 1993), and have limited application in kinesiological EMG as they are primarily designed to measure single muscle fibre activity (Soderberg and Knutson, 2000). Surface electromyography (sEMG) has been employed extensively in biomechanical applications to describe and quantify a muscle or muscle group's activity or performance about the knee (Huston and Wojtys, 1996, Baratta et al., 1988, McNair and Marshall, 1994, Kalund et al., 1990, Gauffin and Tropp, 1992).

Surface electromyography is capable of measuring reflex times. Reflex time can be separated into reflex latencies and motor time components (Cram et al., 1998). Latency of a reflex provides information on the ability of a muscle or muscle group to protect a joint (Cram et al., 1998). Myers et al., (2003) demonstrated that muscle reflex latency is small enough to stimulate a protective muscle contraction during active movements. This mechanism is facilitated by the motor neuron which increases the sensitivity of the muscle spindle. Dhaher et al., (2003) investigated reflex activity around the knee to determine if the timing of the reflexes could protect the knee from a valgus perturbation. Their findings showed an asymmetrical pattern with preferential activation of medial versus lateral muscles of the knee.

Timings of muscle activation are the simplest application of EMG and are calculated from the onset and offset of muscle activity, which is based on threshold and baseline levels of muscle activity (Allison, 2003). The EMG amplitude analysis is more complicated during dynamic muscle action due to amplitude calculation, pattern of motor unit activation and geometric factors of the electrode position (Farina, 2006). However, this is still a component of the muscle action and has a bearing on the neuromuscular contribution, particularly within explosive power based muscle actions. Whilst recognising the limitations of dynamic EMG assessment, the importance of EMG evaluation during high intensity explosive actions is well recognised.

2.4.1.1 Skin preparation

Surface electrodes are subject to movement which in turn disturbs the electrode and skin equilibrium (Gleeson, 2001). Electrode gels or pre-gelled electrodes are required to minimise this change by moving the electrode away from the skin so that movement of the skin does not affect the metal- electrode junction and the potential is unaltered (Gleeson, 2001). In addition, it is important to prepare the skin before electrode placement. This is required to reduce the impedance at the electrode-skin barrier (Gleeson, 2001). It is generally accepted that when using surface EMG the minimum skin preparation should be to clean the skin with acetone or alcohol wipes (Gleeson, 2001).

2.4.1.2 Electrode placement

Location of the bipolar sensor is defined as the position of the geometrical centre of the sensor, unless specified otherwise. Orientation is described as the direction of the bipolar sensor with respect to the direction of the muscle fibres (Hermens et al., 2000).

De Luca, (1997) stated that the factors which control the EMG signal can be classified into causative factors. The causative factors have a main effect on the signal. These are separated into two groups: extrinsic and intrinsic. Intrinsic factors are personal, physical and psychological characteristics that distinguish individuals from each other and extrinsic factors concern environmental conditions and the manner in which activities are administered (Hughes and Watkins, 2006). However, the extrinsic factors are those related to the structure of the electrode and its placement on the muscle. They include: the area and shape of the electrode detection surfaces; the distance between the electrode detection surfaces; the location of the electrode with respect to the motor points in the muscle; the orientation of the detection surfaces with respect to the muscle fibres which affects the value of the of the measured conduction velocity of the action potentials and, consequently, the amplitude and frequency content of the signal.

Skeletal muscles do not remain in a fixed position during complex dynamic (sometimes ballistic) movements and the entire muscle belly may not be completely under the skin, but covered by parts of other bellies or tendons and subcutaneous adipose tissue (this is very variable depending on composition and volume). This emphasizes that the selection of muscles for EMG measurement requires careful consideration. In determining the site of placement of the electrode on the skin, a variety of approaches have been applied: (1) over the motor point; (2) equidistant from the motor point; (3) near the motor point; (4) on the mid-point of the muscle belly; (5) on the visual part of the muscle belly; (6) at standard distances of osteological reference points (anthropometric landmarks); and (7) with no precision at all with respect to its placement .

Bipolar surface electrodes have two detection surfaces (Clarys, 2000). For best possible results, the two detection surfaces should be oriented so that the line between them is parallel to the muscle fibres. To accomplish this arrangement, it is assumed that the muscle fibres act along a line and that the muscles have a single arrangement of unipennate fibres. In some muscles, neither of these conditions is satisfied; in such cases it is advisable to place the electrode so that the line between the detection surfaces points to the origin and the insertion of the muscle. This orientation gives for consistent landmarks, so that the future placement of the electrode will have near-similar orientations and reduce the variation in EMG signal among the myoelectric measurements obtained from different muscle actions (De Luca, 1997). Consequently, four main methods are presented that conform to these requirements:

- The electrode should be placed over the visual midpoint of the contracted muscle (Clarys, 1985).

- The electrode should be placed in relation to standard distances from reference point i.e. anthropometric landmarks (Clarys, 2000).
- The electrode should be placed over the midline of the muscle belly between the nearest innervations zone and the myotendonous junction (Clarys and Cabri, 1993, Basmajian and De Luca, 1985, Gleeson, 2001)
- A combination of these approaches (Clarys, 2000).

The consequences of electrode location on determination of muscle fibre conduction velocity and median frequency estimates have been discussed in the Clarys (2000) study; the most stable and most reliable EMG values are to be obtained from the muscle belly area between the motor point and the most distal tendon (Clarys, 2000). It follows that the position of the detection electrode must be chosen very carefully to minimize errors (Clarys, 2000). The electrode should not be placed near or over the myotendonous junction and near the lateral border of the muscle as this electrode placement could possibly be effected by cross-talk (De Luca, 1997).

2.4.2 The reliability of the EMG

Current reviews have confirmed the usefulness of sEMG investigation in various clinical studies which have analyzed muscle function (Soderberg and Knutson, 2000) and evaluated movement disorders (Pullman et al., 2000). Clinical examination of muscle activation and function is often performed at sub-maximal and (if possible) at maximal levels. For this reason, the EMG behaviour at different force levels is of particular importance. Research findings on the reliability of surface amplitude (Kollmitzer et al., 1999, Mathur et al., 2005, Yang and Winter, 1983, Rainoldi et al., 2001) and frequency values (Kollmitzer et al., 1999, Rainoldi et al., 2001, Mathur et al., 2005) are conflicting depending on the experimental set-up and the type of muscle examined (Knutson et al., 1994). Previous studies have shown that reliability may differ not only between muscle groups but also between various components of the same muscle group (Kollmitzer et al., 1999).

The selection of ambient conditions in which the EMG data are gathered must be given careful consideration. For example the area should be quiet, private, and free of drafts in order to avoid spurious muscle tension due to a startle reaction to loud noise or what may be perceived as a loss of personal privacy and modesty (Iacono, 2004). In addition, surface EMG is influenced by physiological properties such as motor unit discharge rates and muscle fibre membrane characteristics, as well as non-physiological properties such as electrode size, shape and placement (Farina et al., 2004). Day to day variation in EMG recording might be associated with differences in electrode reapplication such as minor changes in the position of the recording electrodes over the muscle and differences in skin preparation (Kankaanpaa et al., 1998). Therefore it is important to determine the reliability of measures derived from the EMG signal for both clinical and research settings, especially when used to determine differences in performance over time in the same individual and differences between individuals (Mathur et al., 2005).

The findings of Claiborne et al., (2009) also illustrated that the EMG measures retained high levels of reliability for most of the observed muscles. Although the studies addressing EMG signal reliability present outcomes from varied methodology and different muscles, there appears to be moderate to high reliability values for the majority of the sampled muscles. Good EMG outcome reliability has been shown between trials for isokinetic exercises for the knee extensors and flexors during concentric and eccentric actions

(Finucane et al., 1998, Larsson et al., 2003). The faster velocities of 1.31 $rads^{-1}$ and 1.83 $rad.s^{-1}$ produced acceptable reliability for the isokinetic conditions (<16% of coefficient of variation) and good reliability (<12%), respectively, for the medial gastrocnemius, therefore it was concluded that the squat jump provides a standardised and reproducible reference EMG value for the triceps surae for use as a normalisation method (Ball and Scurr, 2010). A recent study of Lacourpaille et al., (2012) has suggested that inter-day reliability of EMD, was good (coefficient of variation ranged from 6.8% to 12.5%, i.e. SEM lower than 0.79 ms). These results indicate that the stimulus intensity needs to be standardized to perform longitudinal evaluation and/or to make between-subject comparisons.

In study of Mathur et al., (2005), moderate to high reliability (ICC=0.59-0.88 for MDF; ICC=0.58-0.99 for amplitude) was found for initial and final median frequency (MDF) at 80% and 20% MVC for all three muscle groups (rectus femoris RF., vastus lateralis VL. and vastus medialis VM.) which is in agreement with previous findings of reliability of the quadriceps muscle (Roy et al., 1989), elbow extensors (Bigland-Ritchie and Woods, 1984) and trunk extensors (Elfving et al., 1999). It has previously been shown that the variability associated with repeated contractions differs among the superficial muscles of the quadriceps (MacIntyre et al., 1998, Polgar et al., 1973, Roy et al., 1989). The position of the thigh may account for the greater variability of the EMG recording in VL and VM during knee extension. A slight internal or external rotation at the hip can change the extent to which each of these muscles is recruited thereby increasing between-day variability (MacIntyre et al., 1998, Mannion and Dolan, 1996).

The findings reported by Kellis and Katis, (2008) indicated a moderate to high reliability (The ICCs ranged from 0.44 to 0.98) of median frequency (MF) of hamstring muscles during ramp isometric contractions. It also appears that reliability was higher at lower MVC levels whereas BF EMG outcomes were generally more reliable compared with those from ST (Kellis and Katis, 2008). Monitoring of surface EMG activity provides an easy and direct evaluation of hamstring activation as opposed to torque tests which provide only the resultant moment exerted around the joint (Kellis, 1998). Interpretation of these findings should take into consideration: first, the known variability of the surface EMG signal; second, the electrodes removal between the two testing sessions and third, that ramp contractions are characterised by force changes during contraction which may cause increased EMG signal variability, compared with steady contractions (Kellis and Katis, 2008). It can be concluded that when clinical and quick evaluation of hamstring muscle activation is necessary, surface EMG can be used with acceptable reliability.

Although a number of factors can affect the reliability of EMG outcomes, such as electrode placement, skin preparation, position of the limb and subject performance, the finding of Mathur et al. (2005) study show that outcomes of median frequency (MDF) and amplitude of surface EMG can be reliably measured across days. Furthermore, there was good reliability for mean frequency (MNF), median frequency (MDF) and root mean square (RMS) for the active muscles during static contractions (Aaras et al., 1996, Dedering et al., 2000, Ng and Richardson, 1996, Larsson et al., 2003).

Unfortunately, the manner in which EMG has been used to assess neuromuscular response characteristics in terms of instrumentation, signal processing, and data acquisition has varied and at times becomes quite confusing making interpretation challenging; no standardized procedures currently exist in this regard (Shultz and Perrin, 1999). The most important factor when assessing neuromuscular response characteristics with EMG is not necessarily which methods are used, but whether the methods are reliable. It is important to recognise that reliability very depending upon joint movement, velocity, muscle exhilaration and type of action.

2.4.3 EMD measurement

EMD is described as the latency between the onset of electrical activity in a muscle and the onset of force generation by that muscle's contraction (Yavuz et al., 2010). In addition, EMD is termed as a motor time or motor execution time and is a sub-component of reaction time (Cavanagh and Komi, 1979, van Ingen Schenau et al., 1992). It has been proposed that EMD is relatively constant irrespective of the change of movement complexity (Cavanagh and Komi, 1979) and movement duration (van Ingen Schenau et al., 1992) although it might be lengthened after fatigue (Marsh and Martin, 1995, Vos et al., 1991).

EMD measurements may be performed by voluntary or electrically evoked muscle activation (Hopkins et al., 2007). Measured voluntary strength depends highly on the degree of % motor unit activation (Belanger and McComas, 1981). Both the level of voluntary neural drive or motor unit recruitment and the level of activation or frequency of stimulation govern % motor unit activation. According to Backman and Henriksson, (1988) the ideal way to measure the contractile capacity of a muscle is to record the force developed during supramaximal electrical stimulation of the nerve innervating the muscle. When an electrical stimulus is applied to a motor nerve near the muscle, the resultant muscle force is free of any inhibitory influence from above the point of stimulation. On the other hand, force or torque measured during a voluntary action is the result of neuromuscular influences from the brain and inhibitory reflex influences from the spinal cord in addition to the maximum force producing capacity of the muscle. However, only small muscles that are supplied by a single nerve can be relatively innocuously stimulated transcutaneously (Backman and Henriksson, 1988).

The major finding of Zhou et al., (1995) was that EMD of involuntary **actions** is significantly shorter than that of **voluntary actions**. As suggested by Cavanagh and Komi, (1979), the major portion of EMD is the time required for the contractile component to stretch the series elastic components of the muscle. It is understandable that the muscle which possesses a higher rate of force development will require less time to increase tension to the threshold level of only a few newtons. If EMD depends primarily upon the contractile properties of the motor units recruited at the beginning of an action, according to the size principle (Somjen et al., 1965), the longer EMD found at lower stimulation level could be explained as the recruitment of smaller (possibly slow twitch) motor units, and the larger (possibly fast twitch) motor units with higher excitation threshold would be responsible for the shorter EMD found at higher stimulation level. However, during maximal voluntary actions in most studies, the participants were asked to exert the required force as quickly as they could. As has been indicated in the literature, the low threshold units may not participate in the rapid actions which recruit the high threshold units (Grimby and Einarsson, 1987). If this is the case, the motor units recruited in the fast voluntary actions could be mainly the fast twitch units.

The timing and phasing of muscular activity has been employed to determine muscular response characteristics such as reaction time (Huston and Wojtys, 1996, Lofvenberg et al., 1995, Eccles, 1981) and electromechanical delay (EMD) (Bell and Jacobs, 1986, Winter and Brookes, 1991). Latency or muscle reaction time refers to the time it takes from the onset of the stimulus for the action potential to reach the intended target muscle, as indicated by electrical activity recorded in the EMG signal (LaLoda et al., 1974). In the EMD studies, a mechanical device or contact switch can be interfaced with the EMG to accurately mark when the stimulus occurs and thus provide reliable measures. It is possible that providing more practice in this specific direction during the pre-testing procedures could improve reliability of outcomes (Almosnino et al., 2009).

The study of Hopkins et al. (2007) compared gastrocnemius EMD during voluntary and involuntary contractions and assessed the intra-session reliability of each set of measurements. EMD was greater in the voluntary condition compared to the involuntary condition. Intra-session reliability for each condition was high (involuntary ICC (2,1) = 0.977; voluntary ICC (2,1) = 0.972), therefore reliability within a measurement session was good for each of the conditions (Hopkins et al., 2007). Inter-session reliability of EMD and torque of the dominant and non-dominant elbow flexors has also been demonstrated to be good with no discernable difference between the dominant and non-dominant arms during isometric and isokinetic muscle actions repeated over five consecutive days (Howatson et al., 2009). Almosnino et al., (2009) has also reported that no significant differences in EMD values were observed between two testing sessions in the neck muscles. The findings of excellent inter-session reliability of the EMD measurement in maximal isometric knee extension has previously been determined in the study of Zhou et al., (1996) who performed two tests separated by one week and the reliability coefficients for EMDmax EMDVL and EMDRF were 0.98, 0.97 and 0.98, and for PT, and rate torque development were 0.85 and 0.90, respectively.

There has been some suggestion in the literature that stretching prior to testing may influence torque and EMD after fatigue. Esposito et al. (2009) have recently demonstrated that after stretching EMG parameters return to their pre-fatigue values quicker than if stretching does not occur. These findings suggest that there are stretching-induced changes in visco-elastic and contracting properties of the fatigued muscle (Esposito et al., 2009).

It is important to understand that the EMG signal reflects only the electrical activity of the muscle, which is not synonymous with the production of tension. In fact, a natural EMD exists between neural activation of the muscle as recorded electrically by EMG and the actual generation of force (De Luca, 1997, Winter et al., 1980). EMD can be measured using an isokinetic dynamometer interfaced with the EMG to detect and quantify when muscular tension is developed after neural activation. However, to use signal averaging, data must be acquired at the same precise time and duration across all trials. This can be accomplished through a trigger-sweep data-collection mode using a mechanically reliable triggering device to clearly define when a trial begins or ends (Shultz and Perrin, 1999).

Variability in EMD may be associated with factors such as fibre-type composition and firing rate dynamics of the muscle, velocity of movement, viscoelastic properties and length of the muscle and tendon tissues, activity state, and coactivity of other muscles (De Luca, 1997, Soderberg and Cook, 1984). EMDs reportedly vary anywhere from 30 to 50 milliseconds (Winter et al., 1980) to as much as a few hundred milliseconds (De Luca, 1997). This time lapse, and the need to increase sufficient muscular tension rapidly enough to provide dynamic joint stability, makes EMD a key consideration when investigating factors associated with injury risk.

When processing methods are used to determine muscle activity onset, it is important to realize that any time the raw signal is processed or filtered, a loss of EMG information results and the actual rise time of the signal may be significantly altered. Such processing outcomes affect the researcher's ability to determine the exact time of muscle activity onset (Winter et al., 1980, Soderberg and Cook, 1984). Many techniques have been used to detect the end point of EMD whereas the identification of the onset of EMD is also of considerable interest. To accurately determine the onset of muscle activity, the clinician or researcher must be able to confidently and consistently identify when EMG activity begins or significantly deviates from static or baseline activity. To do so, the EMG signal must exceed a threshold that can be defined in some way, either visually (subjective) or by a statistically predetermined level (objective) (Shultz and Perrin, 1999). As is true in most EMG methodology, while there is no universally accepted method for determining precisely when muscle activity onset occurs, a number of methods have been used to aid in this determination (Winter et al., 1980).

One subjective method is to use the raw signal along with visual recognition, using subjective criteria to determine when muscle activation occurs or to mark the point at which EMG activity begins or changes abruptly from baseline activity (Winter et al., 1980). The subjectivity of this assessment poses serious threats to measurement reliability, particularly between investigators (Shultz and Perrin, 1999). Furthermore, under conditions where the muscle is already contracting and considerable baseline activity is present, the exact moment muscle activity deviates from baseline is often obscured and difficult to determine visually (LaLoda et al., 1974). An alternative, more objectively defined method is to use a computer-assisted analysis program to identify a muscular event based on statistical criteria (Shultz and Perrin, 1999). An example of a computer assisted analysis is to take a representative sample of the baseline activity, statistically determine the mean value and standard deviation of the signal, and then use standard deviations from average baseline activity as the threshold for detection (De Luca, 1997). Using a standard deviation threshold allows the researcher to be 95% confident that a significant change has occurred in muscle activity that is not a result of random occurrence. Onset is traditionally determined by calculating the mean baseline level of the EMG signal and then using a ±15 μV deviation from the baseline (Zhou et al., 1995). The classification of the end point of EMD (defined as the initiation of either movement or force development) is more difficult to define and Zhou et al., (1995) defined the end point of EMD as the onset of torque development as defined as 9.6-N·m.

The effect of training on neuromuscular performance has previously been studied. Grosset et al., (2011) have showed that endurance training leads to a significant decrease in EMD. In addition, Kubo et al. (2001) reported a decrease in EMD after isometric training, but Zhou et al. (1996) found no changes in EMD following sprint training. Similarly Hakkinen and Komi, (1983) reported no significant differences in EMD values calculated under reflex contraction before and after 16 weeks of strength training. Those authors who reported changes in the EMD with training mainly attributed this change to alterations in tendon structures; the stiffness of the tendon always increased with any form of physical activity. Tendon stiffness has been reported to increase after 12 weeks of treadmill endurance training (Buchanan and Marsh, 2001) and after 12 weeks of isometric strength training of knee extensors (Kubo et al., 2001).

In summary, the absolute measurement of muscle response times via sEMG can be influenced by a number of factors. Each of these factors alone can result in significant variations in latency measures that may obscure or confound clinically significant variations (Shultz and Perrin, 1999). Unfortunately, the manner in which sEMG has been used to assess neuromuscular response characteristics in terms of instrumentation, signal processing, and data acquisition is varied and at times quite confusing and challenging for comparison; no standardized procedures currently exist in this regard. Additionally, many research papers fail to adequately report their procedures, which prevents others from being able to replicate or validate their findings (Redfern, 1992). From the limited research available, it appears that a sex difference may exist in some aspects of neuromuscular responses. However, further research is needed to explore these differences at the knee and their potential role as predisposing factors to the higher incidence of anterior cruciate ligament injuries in females. The evaluation of neuromuscular response characteristics around a particular joint can assist the clinician or researcher in understanding muscular activation and recruitment patterns both during and after a loading stress to the joint. In fact, a natural EMD exists between neural activation of the muscle as recorded electrically by EMG and the actual generation of force (De Luca, 1997, Winter et al., 1980). EMD can be measured using a force transducer (or similar device) interfaced with the EMG to detect and quantify when muscular tension is developed after neural activation. This delay can be quite variable due to factors such as fibre-type composition and firing rate dynamics of the muscle, velocity of movement, viscoelastic properties and length of the muscle and tendon tissues, activity state, and coactivity of other muscles (De Luca, 1997, Soderberg and Cook, 1984, Winter et al., 1980). EMDs reportedly vary anywhere from 30 to 50 milliseconds (Winter et al., 1980) to as much as a few hundred milliseconds (De Luca, 1997). Considering this additional time lapse and the need to develop sufficient muscular tension rapidly enough to provide dynamic joint stability, EMD should be considered when evaluating muscular responses to an imposed perturbation or injurious stress.

2.4.4 Age and sex differences in EMD

EMD in the study of Falk et al., (2009) was consistently longer in boys than in men during flexion and extension as was the time to maximal rate of torque development. An age-related decrease in EMD has previously been reported in maximal elbow flexion and in plantar-flexion twitch contraction (Asai and Aoki, 1996, Grosset et al., 2005). Using different types of muscle actions, Cavanagh and Komi, (1979) demonstrated that, in adults, it is mainly the series-elastic component (muscle–tendon stiffness), and not the excitation–contraction coupling, that determines EMD. Indeed, lower musculo-tendinous stiffness has been reported in 7- to 10-year-old boys compared with adults during plantar flexion (Lambertz et al., 2003). However, Cornu and Goubel, (2001) could not show these differences during elbow flexion. Moreover, in a recent study (Grosset et al., 2009), musculo-tendinous stiffness changes could account only for $<20\%$ of the variance in EMD changes. Thus, it is unlikely that boys' longer EMD in the study of Falk et al., (2009) is solely due to their more compliant muscle–tendon complex. More likely is the proposition that factors such as lower muscle activation and lower muscle-fibre conduction velocity in boys (Halin et al., 2003) are also significant determinants of EMD. Further research is needed to elucidate this issue.

Dynamic muscular control of knee joint alignment, specifically differences in muscle recruitment, firing patterns and strength, may be partly responsible for the sex differences in the incidence of ACL injury. Results from Myer et al., (2010) suggest that increased relative quadriceps recruitment, decreased knee flexion ROM, concomitant with increased tibia length and mass normalized to stature are all related to increased ACL injury risk in both children and adults. To what extent any of these factors are related to sex associated risk of injury remains to be identified.

Very few studies so far have specifically addressed sex differences in neuromuscular response characteristics. Electromyographical studies have confirmed that females may have sex-related neuromuscular imbalances in muscle contraction patterns proposed to be related to increased risk of ACL injury (Sell et al., 2004, White et al., 2003). White et al., (2003) examined the differences for muscle force and evaluated EMG power spectra of the quadriceps and hamstring muscles between men and women. They determined that the root mean square (RMS) for quadriceps coactivation in women was higher during knee flexion movements which indicate that women are more “quadriceps” dominant making them more susceptible to ACL injury. Winter and Brookes, (1991) have reported that the EMD of the soleus muscle during plantar flexion and elastic charge time were shorter in the men than in the women whereas for total reaction time, pre-motor time and force time no sex significant differences were observed. Values of total reaction time, pre-motor time and EMD for both men and women were similar to those reported for men by Viitasalo and Komi, (1980). Zhou *et al.* (1995) found significantly longer EMD values in 8-12 year-old (61ms for boys; 58ms for girls) 13-16 year-old (44ms for boys; 47ms for girls) and adult (40ms for males; 46ms for females) females compared to males. Longer EMD in females may be as a result of differences in muscle composition; however, current limited evidence suggests that differences in muscle composition are not sufficient to account for the sex differences. Therefore differences in muscle activation, such as excitation-contraction coupling and muscle fibre conduction velocity have been implicated in the longer EMD for females.

Moore et al., (2002) examined the effects of fatigue on patellar tendon reflex responses in males and females and found that there was an increase in EMD in women after fatiguing protocol, while no change was observed in men. These results suggest males and females may respond differently to fatigue, with males having a greater capacity to compensate for neuromuscular failure when responding to mechanical perturbations. In addition, in a study of Minshull et al., (2007) it was indicated that EMD of biceps femoris muscle increased post-fatigue in women and did not change in men when participants voluntarily contracted their muscles, but it decreased at post-fatigue for both women and men when muscles were stimulated magnetically. Moreover, the findings of Yavuz et al., (2010) indicated that EMD increased at post-fatigue but no difference was observed between men and women. Although direct comparisons are difficult, due to the differences in study designs and protocols, muscle group examined and movement velocity, findings appear similar across studies. The findings of Yavuz et al., (2010) have reported an increase in EMD of the triceps surae muscle group with escalating muscle contraction level and significant increases with fatigue.

A number of adult studies have suggested that males demonstrate a shorter EMD compared to females and have attributed this to greater musculotendinous stiffness in males (Blackburn et al., 2009, Zhou et al., 1995, Grosset et al., 2009). Only one study appears to have explored sex differences in EMD of the knee extensors during eccentric muscle actions (Blackburn et al., 2009) and reported no significant sex difference. However, musculotendinous stiffness and rate of force production (RFP) were greater in males; time to produce 50% peak force (time 50%) was shorter in males, and time 50% was negatively correlated with musculotendinous stiffness. These results suggest that neuromechanical hamstring function in females may limit dynamic knee joint stability, potentially contributing to the greater female ACL injury risk. Whether EMD contributes to the greater relative risk of non-contact ACL injury in females is unclear as further research is needed to explore the sex related changes in EMD, especially during eccentric actions of the hamstrings at a range of velocities.

2.5. FATIGUE

2.5.1 Definition of fatigue

Fatigue occurs in everyday and sporting activities and, in the scientific context, it is accepted that fatigue is the loss of maximal power output when maximal effort is applied (Vøllestad, 1997). Fatigue is commonly understood as a decrease in function and is a class of acute effects that impair performance (Rozzi et al., 1999a). In common parlance, 'fatigue' is a term used to describe the decrease in physical performance associated with an increase in the real or perceived difficulty of a task or exercise (MacInstosh et al., 2005). During exercise, muscle fatigue is described as the inability to maintain the required level of torque (Edwards, 1981). This definition may be interpreted as a 'break point' with the sudden appearance of fatigue and inability to sustain the exercise. However, many neurophysiological mechanisms are 'troubled' before the effect of fatigue becomes evident and these changes sometimes constitute advance warning of fatigue. Furthermore, the initial state of the neuromuscular system is altered as soon as exercise starts. Fatigue then increases progressively until the muscle is no longer able to perform the required task. Fatigue may, therefore, correspond to any exercise- induced reduction in force or power regardless of whether the task can be sustained or not (Bigland-Ritchie and Woods, 1984). Fatigue is a composite, multifactorial phenomenon whose mechanisms are influenced by the characteristics of the task being performed, including type and duration of the exercise, and speed, force and duration of the muscle contraction (Enoka and Stuart, 1992).

During many sporting activities athletes repeatedly perform cutting and landing manoeuvres, without injury to the ACL, due to the adequacy of functional stability at the knee. However, alterations in functional stability may produce a joint that is unable to sense and respond adequately to apply joint forces. Muscular fatigue is considered an important factor in impaired neuromuscular mechanisms, as research has demonstrated its deleterious effects on knee joint laxity as well as both the afferent and efferent neuromuscular pathways (Ribeiro et al., 2007). In response to various exercise protocols designed to induce muscular fatigue, an increase in knee joint laxity has been documented (Weisman et al., 1980).

Although it might be almost impossible to identify the single most important factor contributing to fatigue, this should not deter scientists and clinicians from attempting to resolve many of the issues which surround this concept. Fatigue is commonly defined as any reduction in the maximal capacity to generate force. Although most definitions of fatigue focus on force production, fatigue not only impedes a fibre's capacity for maximal force generation but, importantly, the maximum speed of shortening or lengthening, consequently reducing power output.

2.5.2 Mechanism involved in fatigue

Fatigue is classified as central or peripheral fatigue according to whether it is associated with the central nervous system (CNS) or the peripheral neuromuscular system (Chang et al., 2011). Central fatigue is described as a reduction in neural drive or motor command to the muscle resulting in a decline in force or tension development (Enoka and Stuart, 1992). Peripheral fatigue is defined as a decrease in the force generating capacity of the skeletal muscle due to action potential failure, excitation contraction coupling failure, or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive (Taylor et al., 1997a, Viitasalo and Komi, 1977).

2.5.2.1 Central factors in fatigue

Chaudhuri and Behan, (2000) define central fatigue as the failure to initiate and/or sustain attentional tasks and physical activity. Central fatigue is typically associated with impaired ability to activate motor units. Central fatigue leads to a reduced ability to voluntarily activate the motor units, and thus a decrease in voluntary force generation potential. Therefore, central fatigue can be defined as a progressive, exercise- induced degradation of the ability to voluntarily activate the motor units (Gandevia, 2001).

The presence of central fatigue can be estimated by using percutaneous electrical stimulation (Shield and Zhou, 2004). The examination of a force peak following an electrical stimulation superimposed on the motor nerve innervating the muscle indicates that the voluntary activation was not in fact maximal. Therefore, some motor units are either not recruited or do not fire often enough for the muscle fibres to generate maximal force (Taylor et al., 2006). An increase in the difference between the superimposed peak force and the voluntary peak force over the course of fatiguing exercise may be associated with progressive impairment of voluntary activation and thus with the presence of central fatigue (Taylor et al., 1999). Hence, using electrical stimulation, Schillings et al., (2003) and Kent-Braun, (1999) have shown that 20 and 12% of the loss of torque during a maximal isometric contraction of the ankle dorsiflexors and of the arm flexors are due to central fatigue, respectively. Furthermore, numerous transcranial magnetic stimulation (TMS) studies by Gandevia's group have shown that central fatigue can account for over 25% of the drop in force seen during sustained, maximal contractions (Gandevia, 1998, McNeil et al., 2009, Taylor and Gandevia, 2008). However, central fatigue appears to contribute more significantly to the decrease in force generation during sustained low-intensity exercise (Millet and Lepers, 2004). In fact, Smith et al., (2007) have showed that two thirds of fatigue can be attributed to central (supraspinal) mechanisms during isometric flexion of the forearm at 5% MVC.

The brain has little glycogen reserves and the latter are rapidly exhausted. Although these reserves can be quickly renewed, depletion could influence brain function and, notably, may have an effect on the activity of serotonin (Bequet et al., 2002). The influence of the brain's glycogen levels, neurotransmitter and ammonium on central fatigue and performance has been evidenced in prolonged exercise (over 30 minutes). Nybo and Secher, (2004) indicated that there was a net balance of ammonia across the brain at rest and at 30 min of exercise, whereas 3 h of exercise elicited an uptake in the placebo trial and the glucose trial. Similarly, hyperthermia (a phenomenon sometimes associated with sport and exercise) may reduce the activity of central nervous command (Nielsen and Nybo, 2003).

In a series of studies of fatigue in the ankle dorsiflexor muscles, one laboratory demonstrated that fatigue resistance was similar between men and women in submaximal, intermittent, isometric exercise of progressively increasing intensity (Kent-Braun et al., 2002) in brief (60s) sustained MVCs (Russ et al., 2005), and in intermittent MVCs with a

70% duty cycle (Russ et al., 2008). Deficits in central activation observed with fatigue were similar for men and women in each of these studies. In contrast, this same group found that men fatigued more than women during intermittent MVCs with a 50% duty cycle, and that this difference was associated with greater failure of central activation in men (Russ and Kent-Braun, 2003). When the same participants performed the fatigue protocol under ischemic conditions, the sex-related differences in fatigue and central activation were abolished. Together, these findings highlight the task-specific nature (50% vs 70% duty cycle) markedly altered the difference in fatigue between men and women. These data further suggest a role for central activation failure in sex-related differences in fatigue, when they occur. Because of the sensitivity of the central activation impairment to ischemia, it has been suggested that differences in the exercise-induced decline in the power of hydrogen (pH; acidity) could account for the sex-related differences in central activation.

2.5.2.2 Peripheral factors in fatigue

Studies exploring peripheral fatigue typically examine the integrity of transmission across the neuromuscular junction and whether electrical, mechanical and metabolic fail within the muscle. Effective transmission of signals across the neuromuscular junction and electrical excitation of the muscle membrane is shown by maintenance of compound muscle action potential (M wave) area as force decline. A decline in M wave amplitude does not necessarily indicate signal failure. With higher frequency stimulation, action potentials overlap and M wave amplitude decline from signal cancellation (Fuglevand, 1995). The conduction velocity of muscle fibres also slows with fatigue, resulting in dispersion of motor unit potentials, amplitude changes in the compound response, and increase in M wave duration (Fuglevand, 1995).

In humans it is difficult to examine sites of fatigue beyond excitation of the muscle membrane. Muscle metabolism and biochemical changes have been examined by assessing changes in oxidative and glcolytic enzymes, lactate, phosphocreatine (PCr) and adenosine triphosphate (ATP) from muscle biopsies taken throughout a fatigue protocol (Vollestad et al., 1988), use of nuclear magnetic resonance spectroscopy (Cady et al., 1989) or from estimates of potassium levels (Sjogaard and McComas, 1995). Alterations in calcium handling are usually inferred by comparing changes in twitch and tetanic forces, and rates of contraction and relaxation, whereas failure of excitation-contraction has largely been inferred by exclusion of the other possible sites that can be assessed. The importance of muscle membrane excitability, extracellular potassium accumulation, metabolic changes, reactive oxygen species and calcium handling in the failure of muscle processes (sites that underlie much of the force decline seen during seen during exercise of a healthy nervous system) have largely been understood from studies in reduced preparations and single or skinned muscle fibres, as reviewed by Allen et al., (2008).

The factors involved in peripheral fatigue include alterations in neuromuscular transmission, muscle action potential propagation, excitation-contraction coupling and related contractile mechanisms. During continued contraction, fatigue may decrease the excitability of small-diameter axons. A small decrease in excitation may then lead to inactivation of these axons and a decrease in the amount of neurotransmitter released in the synaptic gap (Krnjevic and Miledi, 1959). These authors have reported an in vitro study in which certain nerve endings of the motorneurons innerving the rat diaphragm were no longer activated after several minutes of electrical muscle stimulation. The authors concluded that the intramuscular oxygen concentration had an influence on propagation of the action potential (AP). The amplitude of motor end-plate potential reduces during fatiguing exercise, as a result of a decrease in the quantity of neurotransmitter (acetylcholine) released by each nerve ending (Reid et al., 1999). This is possibly related to a reduction in the number of exocytotic vesicles and/or a decrease in the quantity of acetylcholine released per vesicle (Reid et al., 1999, Wu and Betz, 1998).

Increases in anterior tibial translation are commonly associated with higher risks of injury for athletes. Muscle fatigue induces a decrease in knee joint stability (Wojtys et al., 1996b) and in knee proprioception (Hiemstra et al., 2001, Lattanzio et al., 1997). Previous studies suggest that the increase in tibial translation is associated with a decrease in motor activity and a resulting reduction in muscle force; it is likely that hamstring reflex activity plays a potential role in knee joint stability. Previous studies demonstrated that muscle fatigue adversely affects the excitability of short latency the increase in tibial translation was due to the delay in muscle reaction time. Likewise, Nyland et al., (1997) demonstrated that muscle activation tended to be delayed after a fatigue protocol consisting of eccentric muscle contractions of the quadriceps muscles.

2.5.2.3 Dynamic stability and the importance of fatigue

Physical activity requires the production of high forces with recruitment levels that maximise the function of each moving part (Green, 1997). The presence of fatigue has been theorised to cause dysfunctions in dynamic stability and therefore increase the risk of injury by affecting afferent and efferent systems as well as muscle function. The manifestations of functional changes occurring with fatigue are multiple and depend on the joint angle, angular velocity, action type (Green, 1997) and on the training status of participant (Hickner et al., 2001).

It is well acknowledged that fatigue negatively affects the ability of muscle to protect joints. Alterations in the afferent input to the motor neurons can potentially affect reactive muscular function and decrease their protective capabilities of the joints (Rizzu et al., 2000). Skinner et al., (1986) described that during fatigue conditions participants had significant decreased proprioceptive abilities. They proposed that this was due to either altered afferent impulses from the muscles themselves or from abnormal stresses in the joint capsule as a result of the muscle fatigue (Skinner et al., 1986).

Although the approaches to studying central and peripheral fatigue produce a different set of challenges both mechanistically and methodologically, whatever approach is taken, the manifestations of fatigue are the same. There is a decline in efficiency of force production, resulting in an increase of the amount of effort to continue or in the continuation being unachievable because the necessary force cannot be sustained. The aetiology of fatigue has been advanced using a variety of clinical populations, sports performers and normal healthy adults. Whether it will ever be possible to identify the limiting cause of fatigue during a task is debatable. What is clear is that fatigue comprises a spectrum of events for which there is no single causative factor, with many factors occupying potential roles in its aetiology. These facts make fatigue such a complex, controversial and interesting issue.

2.5.3 Inducing and assessing fatigue

The fatigue produced by any activity can be assessed by comparing the force of maximal voluntary contraction pre-exercise and post-exercise. In the literature a wide variety of protocols have been used to induce fatigue and a range of methods have been used to monitor the effects. Reported fatigue protocols are either task specific such as running (Rahnama et al., 2003) or muscle action-specific such as those using isokinetic dynamometry (Spendiff et al., 2002). Experiments have therefore used a variety of protocols to induce and test muscle fatigue (Warren et al., 1999). Specificity has been suggested to be of major importance when studying fatigue, so the task should be specific to the exercise in question when used to induce and monitor fatigue.

The hamstrings are especially sensitive to eccentrically induced muscle damage due to their dual innervations and bi articulate arrangement (Croisier et al., 2002). The findings following eccentric fatigue vary as a function of intensity and duration but usually include several effects on performance, such as a drop in torque, a shift to the right of the torque-angle relationship. Findings of Eston et al., (1996) are of interest that post-downhill run changes in muscle tenderness and PT in the knee extensors are reduced by a prior bout of isokinetic eccentric training. Additionally, there was a notable difference in the time course for the recovery of PT and reduction in plasma creatine kinase (CK) activity between the treatment who had a prior bout of eccentric isokinetic training and control participants (Eston et al., 1996) therefore, the effect of fatigue can be reduced with prior exposure to eccentric exercise. Eccentric fatigue alters neuromuscular function and after a decrease of 20% in eccentric hamstrings MVC Nyland et al., (1999) found changes in kinematics of crossover cutting performance. First, a decrease in knee flexion angle was observed at landing; second, an increase in knee internal rolation velocity was found in the impact absorption phase; and finally, the PT angle decreased during propulsion.

The issue of the change in the torque- velocity relationship after repeated eccentric actions has been observed in the literature (Warren et al., 2000, Brockett et al., 2001). Eccentric torque is more fatigue resistant than concentric torque because after an initial decrease in EMG and torque corresponding to the de-recruitment and increased rigidity of the fast twitch fibre, the slow fibres are mainly recruited during prolonged activity. Extensive literature has documented the effects of varying degrees of eccentric exercise and its role in inducing muscle fatigue. Primarily, these investigations have focused on eccentric actions of the elbow flexors (Nosaka and Clarkson, 1997) as well as everyday activities such as downhill stepping (Newham et al., 1986) and running (McHugh et al., 1999). Consistent throughout the literature is that the exercise stimulus must be of sufficient intensity and duration (Tiidus and Ianuzzo, 1983) in order to detect significant skeletal muscle fatigue. Additionally, it has been observed that greater eccentric volumes in concert with high eccentric loads elicit the greatest fatigue response (Warren et al., 1993), but even submaximal workloads are adequate in producing detectable markers of muscle fatigue (Lambert et al., 2001).

Eccentric muscle actions possess several unique features which may explain why they are associated with muscle damage (Eston et al., 2003). During concentric actions, work is done by the muscle, but during eccentric action, work is done on the muscle by the external lengthening forces (Eston et al., 2003). The extensor muscles of the lower limbs eccentrically contract during each stride to decelerate the centre of mass after the foot touches the ground (Walmsley et al., 1978). Eccentric muscle contraction through downhill running has been associated with increased mechanical stress (Iversen and McMahon, 1992). The vertical impact peak force was reported to be higher during short-term downhill running than during level running (Hamill et al., 1984, Dick and Cavanagh, 1987).

The damaging nature of unaccustomed eccentric muscle contractions is well documented (Friden et al., 1983, Newham et al., 1987), and possible mechanisms have been reviewed (Armstrong, 1984). Active isokinetic dynamometers elicit eccentric activations by applying force in the opposite direction to the concentric action of the muscle. Isokinetic flexion and extension exercises do not simulate the joint forces occurring during activities of sport participation. Therefore, this method of inducing muscular fatigue may effectively create fatigued musculature without replicating the joint forces associated with sport activities such as running, cutting, and jumping, which appear to be necessary to induce alterations in ligament laxity. The length of the activated muscles and the forces exerted during eccentric dynamometry are different compared with other modes of eccentric exercise. In addition, submaximal hamstring fatigue is effectively associated with a mechanical loss of knee stability. This decrease in joint stability may explain at least in part a higher risk of ACL injury, especially in fatigued muscles. Therefore, this potential injury risk is primarily might be caused by a decrease in reflex force generation rather than by a moderate increase in latency. Although studies have already found that thigh muscle fatigue leads to larger knee moments (Wikstrom et al., 2004), loss of knee stability (Skinner et al., 1986, Wojtys et al., 1996b) or adverse effects on knee kinematics (Nyland et al., 1994), there is no study with a clear focus on the relationship between neuromuscular control of the hamstrings in terms of reflex components and functional knee stability in fatigued muscles.

A series of eccentric actions lead to a shift in the length-tension relationship to longer muscle lengths with little loss in tension, so that tension at long lengths could actually rise because of the eccentric exercise (Katz, 1939). This has also been found after an isolated hamstring eccentric exercise, inducing a decreased PT joint angle, from 0.91 to 1.04 rad in this case, inducing an average shift of 0.13 ± 0.04 rad (Brockett et al., 2001). A rightward shift of the torque-angle relationship was possibly found as a result of the increased compliance provided by the exercised muscle fibres (Katz, 1939, Talbot and Morgan, 1998, Jones et al., 1997).

2.5.4 The effects of fatigue on the FH/Q ratio

The dynamic control ratio, calculated as the ratio of peak or average torque of the eccentrically contracting hamstring and the concentrically contracting quadriceps during extension of the knee (Hecc/Qcon) should be used (Aagaard et al., 1998, Dvir et al., 1989, Coombs and Garbutt, 2002). This ratio is thought to be an indicator of lower limb capability where the bilateral muscles work against each other in an explosive movement, (Aagaard et al., 1995, Aagaard et al., 1996). In the study of Rahnama et al., (2003), the dynamic torque control ratio was 0.77 and decreased progressively as the duration of 90 min soccer-specific intermittent exercise continued. Furthermore, the magnitude of decline exceeded that observed in the conventional hamstrings: quadriceps ratio. The deficit in hamstrings torque with fatigue is of concern in that it may correspond with a compromised capability for joint stabilisation and, potentially, an increased risk of injury (Rahnama et al., 2003).

Mechanical and metabolic fatigue have been presented as two independent processes but during physical activity they occur concomitantly around the joint and their effects depend on the function of the muscle, the intensity of performance of the activity, and the joint angle and angular velocity specificities due to the arrangements of static and dynamic stabilisers. It has been reported that downhill running was associated with an increased mechanical stress (Iversen and McMahon, 1992). It is also well known that one of the major functions of lower limb muscle tissues is the dissipation of shock loadings during human locomotion (Paul et al., 1978, Radin, 1986). Interestingly downhill running, which involves eccentric contraction, was found to be associated with increased shock propagation from the tibial tuberosity level to the sacrum levels without the development of metabolic fatigue. Downhill running uses a combination of muscles that work eccentrically (e.g. hip extensors, ankle extensors and flexors), which were not previously trained by the isokinetic protocol and may induce fatigue ‘mechanically’, rather than ‘metabolically’. Thus it is likely that damage would naturally be induced in these unprotected muscles, resulting in enzyme release.

During eccentric actions in males, approximately 10% greater reduction in torque was observed in the hamstrings than quadriceps (Rahnama et al., 2003). This difference may be due to the greater efforts of the hamstrings in the control of running activities and for stabilizing the knee joint during foot contact with the ground. If so, then this decline perhaps leads to less control and lower stability of the knee towards the end of the game and thus lead to a greater risk of injury. The incidence of soccer match injuries have shown an increasing tendency as time elapses in both the first and second halves (Ekstrand et al., 2011). One might hypothesize that fatigue might be an explanation for these findings. Studies of physical demands in soccer have shown that fatigue is evident towards the end of a game, and the amount of high-intensity running and technical performance is lowered as a result (Bangsbo et al., 2007, Mohr et al., 2003, Rampinini et al., 2009).

Fatigue in associated musculature has been shown to increase strain magnitudes of bone leading to stress fractures (Arndt et al., 2002, Sharkey et al., 1995). These increased strain magnitudes are likely due to inability of the fatigued muscle to attenuate the forces properly, leading to increased leg shock acceleration and plantar pressures (Radin, 1986, Arndt et al., 2002). McLean et al., (2007) have found a sex difference in knee axial rotation biomechanics during jump landing tasks. The main findings of this study showed that females demonstrated significant increases in initial-contact ankle plantar flexion and in peak knee abduction, peak knee internal rotation, and peak ankle supination angles compared with males and the main effect of fatigue also produced significant increases in peak knee abduction and peak knee internal rotation measures. Gleeson et al., (1995) investigated the effect of a fatigue task (30 reciprocal maximal voluntary actions of the knee flexors and extensors) on isokinetic leg torque in eleven female collegiate soccer players using an isokinetic dynamometer at angular velocity of 3.14 rad.s $^{-1}$. They reported that this fatigue protocol reduced the ability of knee flexors and extensors to generate force by 20% to 60% respectively during concentric muscle actions at 3.14 rad.s $^{-1}$ angular velocity.

The effect of fatigue on two muscle strength ratios: the conventional ratio Hcon/Qcon and dynamic control ratio Hecc/Qcon and the coactivation of hamstrings and quadriceps during isokinetic knee flexion/extension were assessed by Wright et al., (2009). They found that there was a significant increase in both the conventional ratio (0.75 vs. 1.02) and the dynamic control ratio (0.88 vs. 1.08) following fatigue. A significant increase in hamstring coactivation during concentric quadriceps muscle actions following fatigue was also observed (18.6 vs. 21.3%). These data contribute to the literature aiding the future development of the dynamic control ratio and its use in injury prevention and rehabilitation strategies (Wright et al., 2009). Delextrat et al., (2010) investigated the effects of fatigue in males induced by a field test representative of soccer specific movements on different hamstrings/quadriceps ratios in the dominant and non-dominant legs at two different velocities (1.05 and 3.14 $rad.s^{-1}$). The main findings of this study demonstrated significant decreases in the Hcon/Qcon ratio in the dominant leg at 3.14 $rad.s^{-1}$ and in the functional ratio Hecc/Qcon in the dominant leg at 1.05 and 3.14 $rad.s^{-1}$. Additionally, significant correlations were observed between physiological parameters measured during the soccer-specific exercise and Hecc/Qcon only. Oliveira et al., (2009) have verified the effects of heavy-intensity continuous running exercise on the functional and conventional hamstrings/quadriceps ratios in males and they found no differences for the conventional torque ratios, however, the functional torque ratios at 3.14 $rad.s^{-1}$ decreased significantly after running. These results suggested that the FH/Q ratio is more representative of fatigue induced by soccer than the conventional Hcon/Qcon ratio (Oliveira et al., 2009, Delextrat et al., 2010). Heavy-intensity continuous running exercise decreased knee flexor and extensor eccentric torque and functional torque ratios under fast velocities, probably as result of peripheral fatigue (Oliveira et al., 2009).

Small et al., (2010) have investigated the effect of multidirectional soccer-specific fatigue on hamstring muscle strength and angle of peak torque. They found that eccentric hamstring PT decreased significantly during each half time of exercise and the functional hamstring/quadriceps ratio also decreased significantly during each half. In addition, the findings also revealed significant changes for angle of PT for eccentric hamstrings which was significantly higher at the end of each half than the pre-exercise value and there was a time dependent decrease in peak eccentric hamstring torque and in the functional strength ratio which may have implications for the increased predisposition to hamstring strain injury during the latter stages of match-play.

One recent study has indicated that 6 weeks of neuromuscular training significantly increased balance and proprioceptive capabilities of 15-16 year old female basketball players (McLeod et al., 2009). Myer et al., (2008) examined the effectiveness of a trunk and hip focused neuromuscular training programme on knee and hip isokinetic strength in 15 year old girls. After a 10 week training programme the training group improved their hip strength by 16%, whereas the control group reported no significant increases in strength. The authors however, do acknowledge the limitations of their findings as the strength measure was determined from concentric rather than eccentric actions and during open rather than closed chain actions. Further work by this group have also explored differences in the effects of plyometric versus dynamic stabilisation and balance training on lower extremity biomechanics, power and balance (Myer et al., 2005b).

2.5.5 The role of fatigue on neuromuscular performance

In response to muscular fatigue, one study has found an overall decrease in the ability to detect joint motion when extending the joint, and an increase in the onset time of contraction for the medial hamstring and lateral gastrocnemius muscles in response to landing from a jump (Rozzi et al., 1999a). Muscular fatigue is considered an important factor in impaired neuromuscular mechanisms, and research has demonstrated the deleterious effects of fatigue on knee joint laxity as well as both the afferent and efferent neuromuscular pathways (Ribeiro et al., 2007). The importance of altered joint proprioception due to fatigue is a decrease in neuromuscular control (Rizzu et al., 2000). As a consequence of the increased latency periods during the fatigued state, muscles may not be able to respond quickly enough to protect a joint from injury.

There is accumulating evidence that electromechanical delay (EMD) during maximal voluntary muscle actions in the knee extensors and flexors is increased by fatiguing exercise (Gleeson et al., 1998a, Mercer et al., 1998, Zhou et al., 1996). Clinically, alterations in the EMD of the hamstring’s muscle-tendon unit could compromise knee integrity or impair performance by modifying the transfer time of muscle tension to the tibia. Previous studies highlighted the importance of the EMD during physical activities. Vos et al., (1991) observed that changes of the EMD might play an important role in the organization of the movement and probably result in impairment of neuromuscular control, through its relationship with the reflex time. Certainly, sports performance is multifactorial, but EMD, which is a component of the reflex time, is important as it affects muscle response to sudden movements during athletic activities. According to our knowledge, the only published study to explore the possible effects of eccentric exercise-induced muscle damage, following sub-maximal stretch-shortening exercise in males observed no impairment to electrically evoked EMD, despite considerable decrements to volitional peak force and rate of force development capability (Strojnik and Komi, 1998).

There are few adult studies that have examined changes in EMD after fatiguing exercise. Fatiguing exercise lengthens the electromechanical delay (Zhou 1996). Power-trained athletes and other individuals who have a high percentage of fast-twitch muscle fibres exhibit a short EMD under fatiguing exercise conditions (Taylor et al., 1997b, Kamen et al., 1981). The effect of repeated maximal effort isotonic contractions on electromechanical delay was studied by Gabriel and Boucher, (1998) who have defined the period from the onset of the EMG until the beginning of movement as the electromechanical delay and the period from the beginning of movement until the end of the EMG as the second component of the contraction. They reported that over the four day period of 400 rapid elbow flexion trials, there was an increase in the speed of limb movement and the faster contractions were a result of changes in motor unit recruitment during the second component of the contraction, rather than in the electromechanical delay. Yeung et al., (1999) have showed a significant increase in EMD of the vastus medialis following 30 bursts of isometric maximal voluntary contractions. Those authors have attributed the slowing of the speed to the altered crossbridge function during muscle fatigue; the time taken to stretch the series elastic component may have also contributed to the lengthening of EMD. Edman and Lou, (1992) have shown a 9% reduction in fibre stiffness with a 25% depression of the maximal tetanic force during fatiguing stimulation in frog single muscle fibres. Such decrease in muscle stiffness would also potentially lengthen EMD.

Howatson (2010) examined the chronic effects of eccentric fatigue and muscle damage on the biceps brachii in male adults and reported significantly greater EMD up to 96 h following the exercise bout. This finding was despite the apparent return of muscle function and suggests that caution should be taken if a task requiring a fast reaction time or fast generation of high forces is needed following this type of exercise. Zhou et al (1996) also demonstrated a significant increase in EMD following four bouts of 30 s all out cycling exercise in adult males. All of the available adult studies seem to show a significant increase in EMD after fatiguing trials which could predispose the knee to greater injury risk. The mechanisms involved in the increase in EMD after fatigue could be due to the deterioration in muscle conductive, contractile or elastic properties and requires further study. Unfortunately there are no current data available that permit exploration of the sex associated changes in EMD after fatiguing exercise. This data is urgently needed to elucidate the factors associated with the relative risk of non-contact knee injury when the adult is in a fatigued state.

2.6 SUMMARY

ACL injury is serious, involving high costs for the individual which, despite noticeable progress in surgical and rehabilitation procedures, is still characterised by difficulty in returning the athlete to pre injury levels of performance. In relation to developing an injury prevention programme, the first step is to identify and control the risks of injury. The alterations induced by risk factors have been investigated with the conventional ratio. The "conventional" ratio is the most widely reported ratio in the literature and is calculated by dividing the concentric hamstrings PT by the concentric quadriceps peak torque, but it does not appear adequate to highlight changes in dynamic stability due to a lack of functional significance. The FH/Q ratio has been used to investigate the changes in dynamic stability. To calculate the FH/Q ratio the peak eccentric hamstrings torque is divided by the peak concentric quadriceps torque to evaluate the relative ability of the hamstrings to act eccentrically and stabilise the knee. In fact, during knee extension antagonistic eccentric, not concentric, hamstrings co-activation decreases the anterior shear forces induced by the concentric quadriceps muscle group action. Therefore, the FH/Q ratio has been suggested as more relevant.

Neuromuscular and biomechanical factors such as decreased joint angle, increased angular velocity and fatigue play an important role in the aetiology of ACL injury due to their influence on dynamic stability. Based on the small empirical research base, demonstrating an indirect link between muscular and neuromuscular ability and injury incidence a schematic framework for this thesis s demonstrated in figure 2. ACL rupture is most likely to occur near full knee extension during high velocity movement. If it is to be accepted that a low FH/Q ratio may increase the relative risk of injury then it is essential to determine whether the ratio is reduced when: a) approaching full knee extension b) with increasing angular velocity c) in the presence of action-specific fatigue.

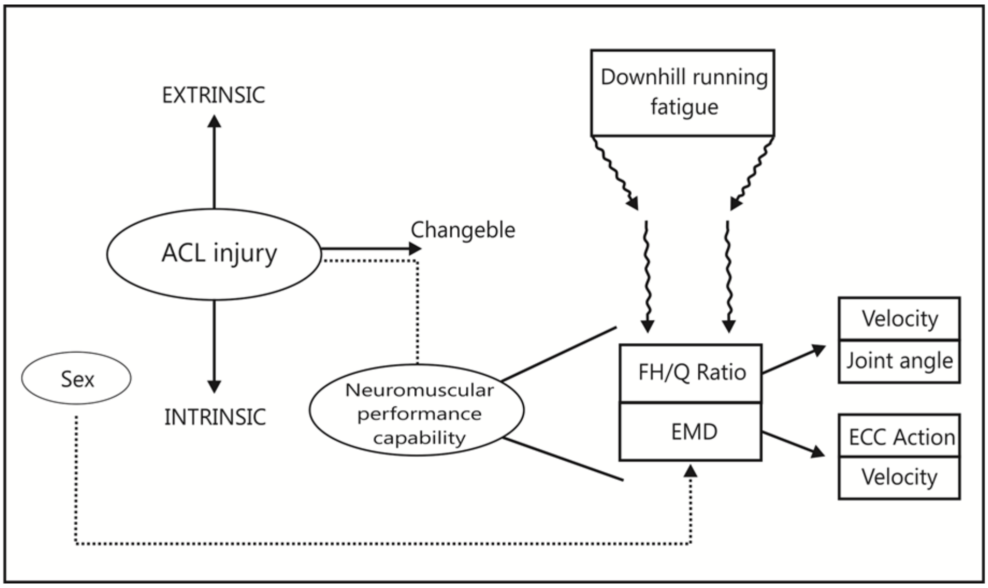


Figure (2) adapted from figure 1 (p. 2) as the conceptual framework for the research programme of this thesis.

The EMD, which is defined as the time interval between the onset of detectable electrical activity at the muscle and the associated force production (Cavanagh and Komi, 1979), has been implicated as a risk factor for knee injury in adults (Blackburn et al., 2009). Electromyographical studies have confirmed that females may have sex-related neuromuscular imbalances in muscle contraction patterns proposed to be related to increased risk of ACL injury (Sell et al., 2004, White et al., 2003). Whether EMD accounts for the greater relative risk in females remains to be identified as there are no studies that have examined sex differences in EMD particularly for the knee flexors pre and post fatigue and particularly following eccentric actions. Further study is needed to explore the changes in EMD pre and post fatigue in males and females, especially following eccentric exercise.

Following physical activity the effects of mechanical and metabolic fatigue depend on the function of the muscle, the intensity of the activity, and the joint angle and angular velocity. The presence of fatigue has been theorised to cause dysfunctions in dynamic stability and therefore increase the risk of injury by influencing afferent and efferent pathways as well as muscle function itself. Although the present thesis is not explicitly exploring the mechanistic basis for fatigue, it may be possible to develop an enhanced understanding from the findings.

2-7 Hypotheses of thesis

Based on the previous literature, it was hypothesised for this thesis that:

1. The FH/Q ratio will be significantly lower in females compared to males.
2. The FH/Q ratio will significantly increase as velocity of movement increases.
3. The FH/Q ratio will significantly decrease with decreasing knee joint angle (closer to full knee extension).
4. The EMD will be significantly longer in females compared to males.
5. The EMD will be significantly longer as velocity of movement increases.
6. The EMD will be significantly different between hamstrings muscle groups.
7. The FH/Q ratio will significantly decrease post-fatigue compared to pre-fatigue task with greater decrease in FH/Q ratio in females compared to males.
8. The EMD will significantly increase post-fatigue compared to pre-fatigue task with a greater increase in EMD in females compared to males.
9. The effects of fatigue on FH/Q ratio will be significantly greater increases with decreasing joint angle (closer to full knee extension).
10. The effects of fatigue on FH/Q ratio will be significantly greater increases with decreasing angular velocity.
11. Irrespective of sex or time, the EMD will be significantly different between hamstrings muscle groups.
12. Irrespective of sex or time, the EMD will be significantly longer as velocity movement increase.

Chapter 3:

General Methods

3-1 *Participants and recruitment*

One hundred and ten healthy males (n=55) and females (n=55) were recruited from the university population (see physical characteristics in Table 3 chapter 4). All participants in the study were aged between 18-35 years, without previous injury to their dominant leg and regularly involved in moderate intensity exercise (at least three times per week). The number of participants was calculated based on statistical power calculations (Vincent, 1995) of the FH/Q ratio and EMD production at each test movement velocity (60, 120 and 240°·s^{-1}) in the DOM limb, a range of sample sizes for each group (males and females) were indicated (see appendix 1) and informed the study design. The University's Research Ethics sub-Committee (RESC) approved all procedures as documented in the laboratory procedures manual (Gloucestershire, 2008). Participants were provided with an information sheet (Appendix 2) to explain the procedures involved in the studies and potential questions were answered by the researcher. They then gave written consent (Appendix 3) in accordance with the University of Gloucestershire sports and exercise laboratory procedures and completed a health questionnaire (Appendix 4). Acceptance to the study was approved if the participants satisfied the acceptance criterion as described in the health questionnaire flow chart (Appendix 5). On each testing occasion the participants were asked to review their answers to the questionnaire and date and sign it again if circumstances had not changed since the health questionnaire was initially completed however, if circumstances had changed the participants were obliged to complete another health questionnaire. Participants visited the laboratory one week prior to testing to familiarise themselves with the laboratory and the experimental procedures. All raw data were stored confidentially in electronic form using ID codes and all participants' results were reported anonymously.

For female participants, menstrual cycle has predominantly been shown not to affect isokinetic strength (Lebrun et al., 1995, Gur, 1997, Janse de Jonge et al., 2001), however changes in knee laxity between different menstrual phases (follicular versus ovulation, ovulation versus luteal) correlated with changes in knee joint loads (Park et al., 2008). Therefore, all testing was conducted during the luteal phase of the menstrual cycle (post ovulation phase, average start and end days 15 to 26) which was self-reported by the participant. During this phase it has been reported that women have reduced knee laxity which may reduce knee joint loads (Park et al., 2008).

The participants were requested not to:

- Participate in strenuous physical activities in the 48 h prior to testing.
- Eat or drink anything other than water in the final 3 h before each visit.
- Drink alcohol in the final 24 h before each visit or take caffeine or medication within the final 12 h before the test.

3-2 *Pilot preliminary work*

Sixteen healthy males (n=8) and females (n=8) were recruited from the university population for the pilot preliminary work to explore and development the appropriate procedures for the determination the following: a) electromechanical delay protocol, b) fatigue protocol, c) angular velocities to be used, d) integration of the EMG system interface signal via a trigger box. The outcome of this pilot preliminary work was that we selected three movement velocities with which the participants were comfortable for measuring EMD and FH/Q ratio. The pilot work also enabled us to ensure that the trigger was simultaneously determining EMG and torque measurement.

3-3 *Familiarisation session*

Stature and body mass were measured on the first visit to the laboratory and leg dominance was determined by asking the participants which leg they would use to kick a ball (Rizzardo et al., 1988). All participants were familiarised with the calibrated Biodex System-3 Isokinetic Dynamometer and the test protocol one week prior to the testing of the main studies. Specifically, as part of the familiarisation procedures, the participants were provided with a careful explanation of all procedures and allowed several sub-maximal warm-ups, plus maximal practices in each test condition.

3-4 *Procedures*

3-4-1 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 and stored for further reference and use. Stature was measured using a Stadiometer (Holtain Harpenden, Crymych, UK) and determined to the nearest millimetre. The participant stood with toes and heels together, without shoes on, and with their back to the stand. The researcher then applied gentle pressure to the mastoid processes while encouraged to stand tall and look straight ahead. Body mass was assessed using calibrated balance beam scales (Weylux Birmingham, UK) and calculation was made to the nearest 100g with T-shirt, shorts and without shoes. These procedures were in accordance to the International Association for the Advancement of Kinanthropometry guidelines (Eston and Reilly, 2001).

3-4-2 Peak torque assessments

Isokinetic concentric and eccentric assessments of the knee extension and flexion were performed on Biodex Isokinetic dynamometer (System-3, Biodex Corp., and Shirley, New York, USA) Figure (3).

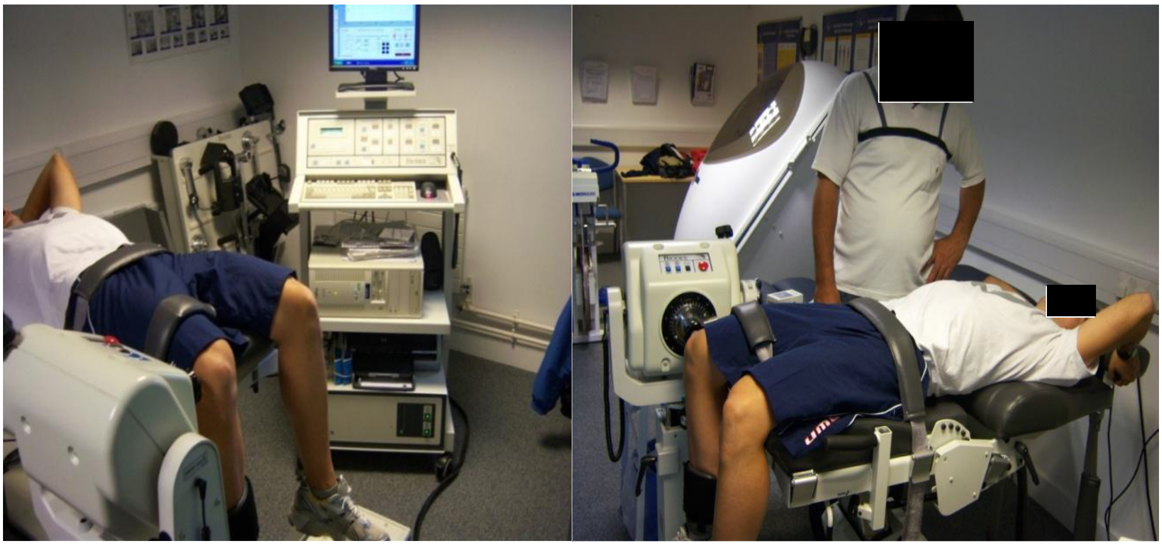


Figure (3) A Biodex System-3 Dynamometer and participant in a supine position during concentric quadriceps test.

Formal assessments were commenced with a standardised warm up consisting of 5 minutes of cycling at 60 W on a Monark cycle ergometer 814E (Varberg, Sweden). The dynamometer set-up for knee extension and flexion was as follows: the dynamometer seatback was tilted to 0° hip flexion. The participant sat on the chair and the seat length was adjusted so that the participant`s legs were hanging freely with the back of the knee at approximately 2 cm away from the edge of the seat. The axis of rotation of the knee was carefully aligned with that of the dynamometer using the lateral epicondyle as an anatomical landmark. Stabilisation straps were applied to the waist and distal femur of the leg being tested (Figure 3) to provide constant conditions and to mitigate any movement which may have confounded the test results. Knee attachments varied according to the participants. The lever arm length was adjusted so that the shin cuff rested comfortably on the tibia, approximately 2 or 3 cm above the malleolus, to allow full dorsi and plantar flexion (Figure 4). The set up of the dynamometer and positioning of the participants were kept consistent between all trials and studies, including seat height settings, seat length, dynamometer height, chair forward slide adjustments and lever arm length settings.

Figure (4) A participant in a prone position during eccentric hamstring test.

PT assessments were made on the dominant leg. Motion ranged from 90° to 0° of knee flexion (0° = full extension) was determined for each participant individually by placing mechanical stops at the beginning and end of their full active range of motion. The range stop control was set as soft (2) so as to reduce the possibility of sudden resistance at the end of each range of motion. 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.

All assessments were performed in a supine position for determination of concentric quadriceps torque (Figure 3) which were undertaken first and then in a prone position for determination of eccentric hamstring torque (Figure 4). Testing occurred at slow ($60°\cdot s^{-1}$), intermediate ($120°\cdot s^{-1}$) and fast angular velocities ($240°\cdot s^{-1}$) for both concentric and eccentric actions with extension always undertaken first. Testing began with the slowest angular velocity ($60°\cdot s^{-1}$) and continued with increasing velocity ($120°\cdot s^{-1}$ following by $240°\cdot s^{-1}$) to reduce the risk of injury (Gaul, 1996). PT was determined during dual phase concentric-concentric actions and single phase eccentric actions using the passive eccentric mode. In the concentric quadriceps measurement participants were instructed to push the lever arm up, and pull it down. However, in the eccentric hamstring measurement participants were instructed to resist the lever arm as hard and as fast as possible, when it moved passively down and then relax when it moved up. Thus the participants` limb was passively returned to the starting position by the dynamometers` lever-arm.

Participants performed three maximal efforts at each angular velocity and 30 s of rest were allowed between movements at different angular velocity to attempt to reduce any potentiation effects. Participants were instructed to push, pull or resist the lever arm as hard and as fast as possible throughout the entire range of motion until they were told to stop. Standardised verbal encouragement was given before each maximal effort and visual feedback of the recorded torque was provided.

3-4-3 Electromyography

The electromyography was quantified with an 8-channel DelSys EMG telemetry system (DelSys Myomonitor III, DelSys Inc., Boston, MA, USA) (Figure 5). Electromyography was used to investigate the activity of the hamstrings during the eccentric hamstrings PT to determine the electromechanical delay. For maximum signal detection each bipolar surface electrode (DE- 2.3 MA; DelSys Inc., Boston, MA, USA) was positioned in the mid-line of the belly of the muscle perpendicular to the muscle fibres because in this location the electromyographic signal with the greatest amplitude is detected (Gleeson, 2001).

Figure (5) A Myomonitor Wireless EMG System.

The biodex square wave synchronization pulse was configurable via the biodex ASA software (Figure 6), thus allowing the triggering of the EMG software. The EMG system interfaced the signal 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 was used to activate the biodex square wave signal output to get the right start signal. The Trigger Module only accepted signals that were between 0 to 5 volts, and could be configured for either positive-edge signals (Figure 7.a) or negative-edge signals (Figure 7.b).

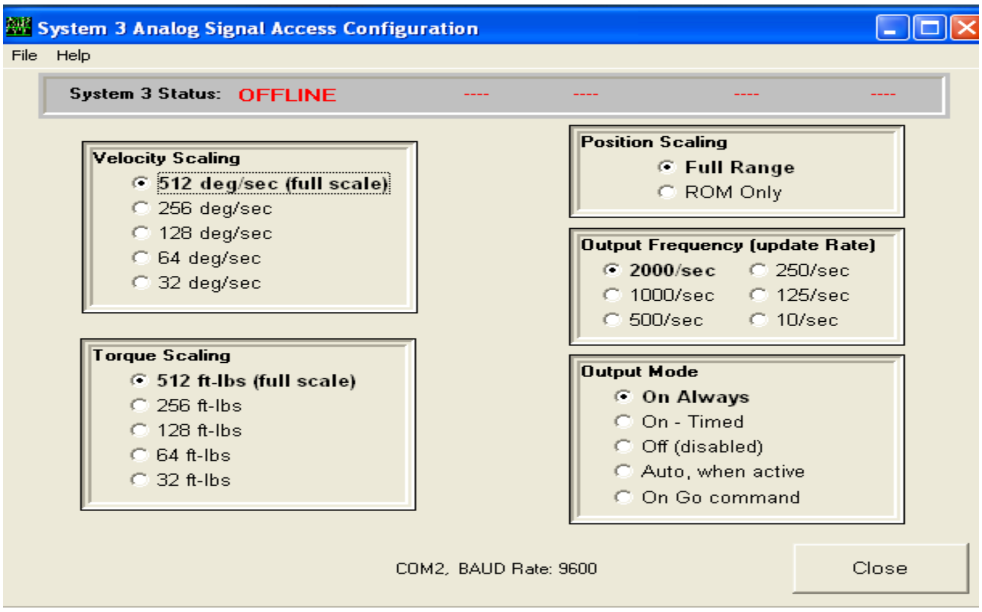
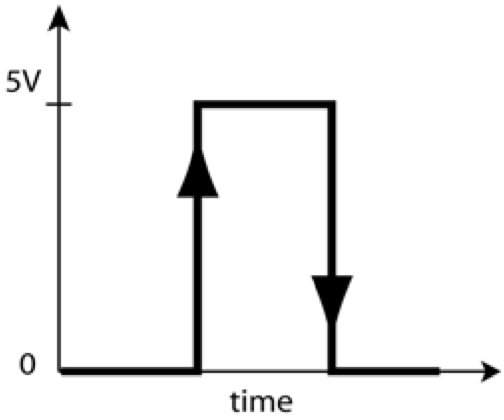


Figure (6) Analog signal access configuration via the biodex ASA program.



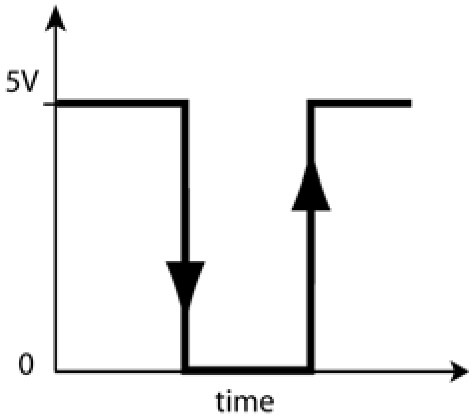


Figure (7.a) Positive-edge or “rising” signal. Figure (7.b) Negative-edge or “falling” signal.

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 was kept in the high state for a minimum amount of time before returning back to the low state. The trigger box (Figure 8) looked for a change in the biodex output square wave signal, so 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 and a light appears on the trigger port. Therefore, the EMG and biodex were completely time aligned.

Figure (8) A Trigger Port on Myomonitor System.

Three electrodes were placed on the dominant limb on the medial and lateral hamstring muscles represented by semitendinosus (ST), semimembranosus (SM) and biceps femoris (BF) as recommended by Finni and Sulin, (2009) (Figure 9).

Figure (9) Positioning of the electrodes

Following the application of surface electrodes participants were instructed to perform eccentric PT assessments of the hamstring muscles from prone position on the dominant leg (using the same isokinetic procedures highlighted in methods section 3-4-2). 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). EMG data is typically collected at 1000 Hz (Dermaux and Sandra, 1999). The EMG unit included 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 standard for the skin preparation was an electrical resistance between the three electrodes of less than 5kΩ. The skin was cleaned and shaved if necessary, so any visible hair was removed. This preparation was completed to improve application of the electrodes and reduce the acceptable impedance to below 5kΩ. An electrolyte electrode gel was applied to maximise conductivity mention using a prevent pen to mark position of electrodes for future testing (Figure 9).

3-4-3 Electromechanical delay (EMD)

The EMD was determined as the time interval between the onset of EMG and force development. EMD was determined using measurements performed in a prone position with a hip angle of 0° on the dominant leg using the isokinetic dynamometer and the surface EMG unit, according to the protocol developed by Zhou et al (1995). Based on this protocol the onset of EMD was determent from the time of the EMG measuerments (ms) which against to the mean of baseline level and +15 µV deviation for the EMG signal and the offset of EMD was determened from the time of eccentric hamstring measurements (ms) which against to the torque development is defined as a 9.6-N·m as described in Figure (10).

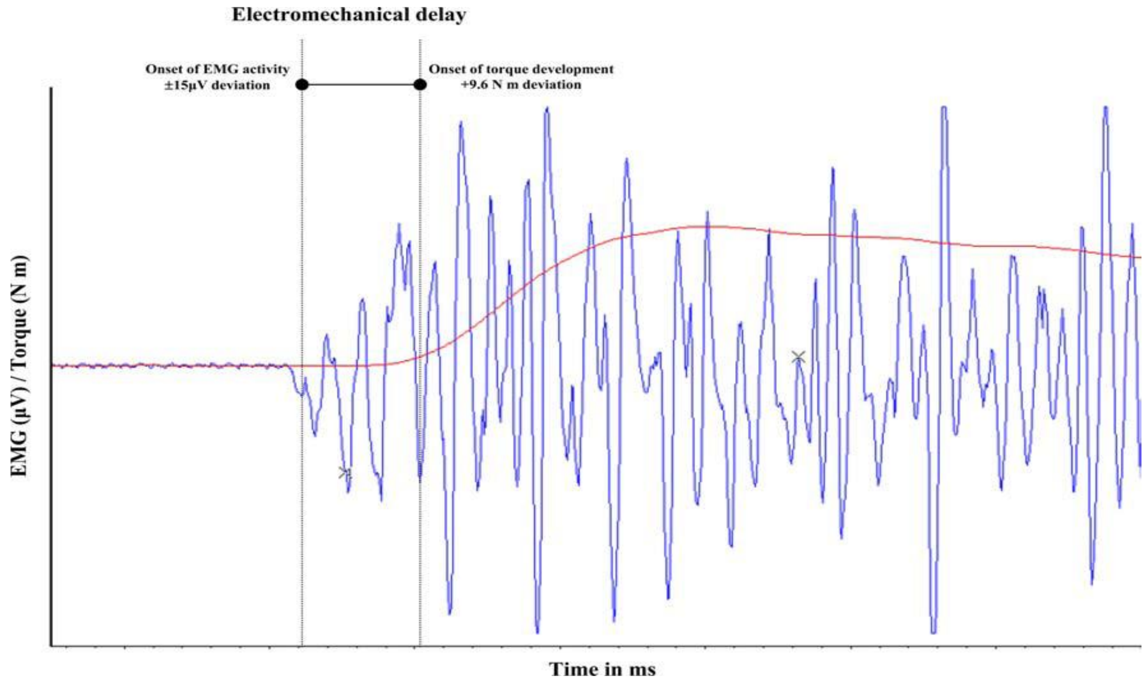


Figure (10) The process used to determine the EMD (taken from Zhou et al. 1995).

The participants were asked to exert maximal voluntary torque as quickly as possible when the light on the trigger box came on which was generated by the trigger system. The contraction force was displayed on an analogue device. The participants were allowed a maximum three rehearsals at three angular velocities (60, 120 and 240°$\cdot$s^{-1}).

3-5 Key outcome variables

3-5-1 Functional hamstring to quadriceps ratio

PT values were recorded during concentric quadriceps and eccentric hamstrings action and later used to calculate the functional hamstring to quadriceps ratio by expressing peak eccentric hamstrings torque to concentric quadriceps (as a ratio) at three angular velocities (60, 120 and 240°$\cdot$s^{-1}) and at three knee angles (15°, 30° and 45°). PT was defined as the highest value obtained during three maximal isokinetic actions.

3-5-2 Electromechanical Delay

The EMG data for each section of the movement during eccentric PT at three angular velocities (60, 120 and 240°·s^{-1}) was normalised against the maximum EMG RMS amplitude recorded in the activity of the hamstrings muscles (semitendinosus, ST; semimembranosus muscles, SM; and biceps femoris, BF) to determine the electromechanical delay in a pre-fatigue state and then again in a fatigued state. To investigate the true EMD in a contraction, the maximal electromechanical delay (EMD max) value was determined as the longer EMD during a maximum of three measurements for three angular velocities.

3-6 Data analysis

Statistical analysis was performed using SPSS (version 17) software package (SPSS Inc., Chicago, USA). The level of significance was set at $P \leq 0.05$ for all tests (See chapters 4-6).

Chapter 4: Study One

Sex Differences in the Functional Hamstring to Quadriceps Ratio

4-1 INTRODUCTION

Non-contact injuries to the anterior cruciate ligament (ACL) in physically active females are increasing annually and proportionately to the number of hours exposed to physical activity and sport. Each year, it is approximated that 80 000 to 250 000 ACL injuries occur in young athletes as increasing numbers of individuals participate in sports (Griffin et al., 2006). ACL injury rates differ by sex in several sports, with women experiencing two to eight times higher injury rates than men in the same sports (Good et al., 1991). A limited number of studies have investigated the possible mechanisms relating to the incidence of ACL injury based on exposure time and have compared male and female athletes competing in similar activities at the same level of competition (Renstrom et al., 2008).

Decreased hamstrings strength relative to the quadriceps (H/Q ratio) is implicated as a mechanism for increased lower extremity injuries (Myer et al., 2004, Knapik et al., 1991). It has been demonstrated that imbalances in hamstrings to quadriceps strength (e.g, H/Q ratio < 0.75) are associated with greater incidence of lower extremity injury in female collegiate athletes (Knapik et al., 1991). Isokinetic testing allows the assessment or the ability of the agonist-antagonist musculature to co-contract during reciprocal extension-flexion motions. This testing assists the researcher in investigating the ability of the antagonists (hamstrings) to ‘‘brake’’ the movement of the agonist (quadriceps) (Wilk et al., 1994).

The hamstring to quadriceps ratio has conventionally been expressed as concentric hamstrings to concentric quadriceps strength (Lund-Hanssen et al., 1996) which does not reflect the *functional* capacity of the knee during dynamic movement and recent investigations have demonstrated that the conventional torque ratio calculated using concentric actions is not relevant for evaluation of joint balance. A FH/Q ratio of about 1.00 has been reported for fast isokinetic knee extension movement, indicating a significant capacity of the hamstring muscles to provide dynamic joint stabilisation during active knee extension (Aagaard et al., 1995). Thus, the use of eccentric torque could provide a more functional index (Aagaard et al., 1998, Coombs and Garbutt, 2002, Rahnama et al., 2003). The ratio of eccentric hamstring torque-to-concentric quadriceps torque (FH/Q ratio) may be the most appropriate means of describing the balance of strength about the knee (Aagaard et al., 1998, Aagaard et al., 1995).

It has been recognised that the FH/Q is influenced by numerous factors, such as maturation, sex and the method of calculation (Ahmad et al., 2006, De Ste Croix et al., 2007, Hewett et al., 2007). There are also a number of methodological issues that may influence the FH/Q ratio, in-particular the hip joint angle and the movement velocity. Many researchers have stated that women tend to land or decelerate with more knee extension than their male counterparts (Fillyaw et al., 1986, Wilk et al., 1994). This is believed to be a contributing factor to the increased incidence of ACL injuries in women. When landing with the knee closer to extension it is thought to decrease the ability of the hamstring muscles to prevent the quadriceps from pulling the tibia in an anterior direction, and thereby increasing the load on the ACL (Knapik et al., 1991).

Isokinetic dynamometers allow the objective assessment of muscle strength in both concentric and eccentric exercise modes, across a range of angular velocities. PT data from isokinetic assessments can be used to calculate ratios to evaluate the reciprocal and bilateral balance of strength at the knee joint. In addition, the velocity of isokinetic actions may influence the interpretation of the results, considering the differences between slow and fast velocities (Gerodimos et al., 2003, Hewett et al., 2007). Few studies have examined sex differences in dynamic knee joint stability; evaluation of isokinetic eccentric antagonistic strength relative to concentric agonist strength may be of value in describing the maximal potential of the antagonistic muscle group (Coombs et al., 2002).

A FH/Q ratio of about 1.00 has been reported for fast isokinetic knee extension movement, indicating a significant capacity of the hamstring muscles to provide dynamic joint stabilisation during active knee extension (Aagaard et al., 1998). The quadriceps, through the anterior pull of the patellar tendon on the tibia, contributes to ACL loading when knee flexion is less than 30° to 45° (Markolf et al., 1978). The FH/Q ratio is velocity and joint angle dependent (Aagard et al., 1998), and the current study builds on the work of Sauret, (2009), who suggested that the functional ratio should be calculated at specified angles to avoid differences in PT between quadriceps and hamstring due to varying joint angle. However, sex differences in functional ratio, taking into account angle and velocity, remain to be investigated, and may reflect predisposition to injury (Croce et al., 1996).

Few studies appear to have examined angle specific FH/Q ratios across a range of velocities and in both sexes. Aagaard et al., (1998) have used female and male track athletes to investigate joint angle-specific FH/Q ratio and reported an increase in the FH/Q ratio with decreased joint angle at 50 degrees of extension. However, the previous literature is limited in sample size (especially as we have 110 participants in current study) and also they ignored joint angles lower than 30 degrees, where dynamic stability is often challenged. Coombs and Garbutt, (2002) used a small sample of 9 female and 6 male recreational athletes to calculate joint angle-specific FH/Q ratio values throughout 90 degrees range of movement and found increasing FH/Q ratios as the joint moves closer to full extension. Kellis and Katis, (2007) reported that the FH/Q ratio of males significantly increased as the knee extended at increased angular velocities reaching a value of 3.14 ± 1.95 at near full extension. This would suggest a compensatory mechanism in both males and females with an increased FH/Q ratio when the joint is near full knee extension and the movement velocity increases. However, this hypothesis requires further investigation with the hip in a functionally relevant joint position (e.g., flexed at about 10º), and employing much larger sample sizes over a range of movement velocities.

Within current literature torques (i.e., PT) achieved at different angles are being used to represent a ratio which should be describing the ability of opposing torques to counteract each other (i.e., at the same joint angle). This ambiguity clearly does not help in elucidating the functional role that these muscles play in stabilizing the knee. Furthermore, the joint angle where non-contact ACL injury is mostly likely to occur is not at the point where PT is generated. Peak concentric and eccentric torque production is likely to occur in the mid-late range of the movement (around 30-80º of knee flexion), whereas it is well recognised that injury is likely to occur when the knee is closer to full extension (0-30º of knee flexion). Based on this knowledge it would seem more appropriate to calculate the FH/Q ratio using angle specific torque values close to full extension. It is clear that more data are required on the FH/Q ratio, especially using angle specific data and in females.

Whether this will change our understanding of associated differences in dynamic knee stability, and the susceptibility to knee injury, remains to be established.

The present study examines the sex differences in the FH/Q ratio that appear to be associated with reduced knee stability and an increased risk of ACL injury. Comparisons also take account of potential counfounding factors of joint angle and angular velocity.

4-2 METHODS

4-2-1 Participants

One hundred and ten healthy males (n=55) and females (n=55) were recruited from the university population (see physical characteristics in Table 3).

4-2-2 Study design

This study was designed to investigate the FH/Q ratio in a non-fatigued state between males and females groups across a range of three knee joint angles (15°, 30° and 45°) and three angular velocities (60°, 120° and 240°$\cdot s^{-1}$). Data were collected as described in Figure (11).

40 minutes		
6-8 min	17 min	15 min
Warm-up	Concentric Quadriceps testing. 3 Reps @ 60°$\cdot s^{-1}$ then 30s rest 3 Reps @ 120°$\cdot s^{-1}$ then 30s rest 3 Reps @ 240°$\cdot s^{-1}$ then 2min rest To change this position	Eccentric Hamstring testing. 3 Reps @ 60°$\cdot s^{-1}$ then 30s rest 3 Reps @ 120°$\cdot s^{-1}$ then 30s rest 3 Reps @ 240°$\cdot s^{-1}$ then 2min rest cool down (Finish all testing)
Cycling	**From supine position**	**From prone position**

Figure 11: Timeline for data-collection.

4-2-3 Familiarisation

The participants` first visit to the laboratory was designed to familiarise them with the testing procedures, equipment and environment. The concentric and eccentric tasks were explained and demonstrated and the participants were invited to experience both concentric and eccentric actions. All participants were familiarised with test protocol one week prior to the testing of the main tests. They were asked to perform several sub-maximal eccentric and concentric actions until torque could be achieved consistently. Finally they were asked to perform three maximum efforts. All participants were encouraged to give a maximal effort for each action by using both visual feedback and strong verbal encouragement to improve consistency during the subsequent testing sessions (see section 3-3 in chapter 3).

4-2-4 Test session

4-2-4-1 Warm-up

The test session was 7 days after the familiarisation session. The participants warmed up for 5 minutes by cycling at 60 W on a Monark cycle ergometer 814E (Varberg, Sweden). To complete the warm up and to familiarise them with the equipment and all testing procedures, they were asked to perform 3 sub maximal action specific repetitions and 2 maximal repetitions at $120°\cdot s^{-1}$ prior to the concentric and eccentric tests.

4-2-4-2 Concentric and eccentric torque measurements

Concentric quadriceps and eccentric hamstring torque data were collected as presented in section 3-4. Participants performed 3 maximal efforts from supine position for concentric quadriceps and prone position for eccentric hamstring at slow ($60°\cdot s^{-1}$), intermediate ($120°\cdot s^{-1}$) and fast angular velocities ($240°\cdot s^{-1}$) and 30 seconds of rest were allowed between movements at different angular velocity. Participants were instructed to push, pull or resist the lever arm as hard and as fast as possible throughout the entire range of motion until they were told to stop. Standardised verbal encouragement was given before each maximal effort and visual feedback of the recorded torque was provided (all isokinetic procedures highlighted in general methods section 3-4-2).

4-2-4-3 Cool down

Immediately after the testing, participants were invited to complete 2 min cool down on the cycle ergometer at low intensities and stretch the quadriceps and hamstrings muscle groups.

4-2-5 Data analysis

For this study, analysis was performed for the independent variables of knee angle, knee angular velocity and sex (3 x 3 x 2) using a mixed-factorial analysis of variance (ANOVA) to determine the main and interaction effect on the dependent variable of the concentric quadriceps and eccentric hamstrings ratio based on angle specific PT values. The three independent variables include two within-subjects factors: knee angle (15º, 30º and 45º) and velocity (60°, 180°, and $240°\cdot s^{-1}$) and a between-subjects factor of sex (male and female).

4.3 RESULTS OF STUDY 1:

- **FH/Q ratio and influence of sex, angular velocity and knee joint angle**

4.3.1 Physical characteristics

The physical characteristics (age, stature, and body mass) of 110 healthy males (n=55) and females (n=55) are presented for each group in Table 3. There were no significant differences between males and females in age but males were significantly ($p<0.05$) taller and had greater body mass.

Table 3 Participant physical characteristics for study 1 and 2

Variables	Group	Mean	SD	Minimum	Maximum
Age: (y)	Males	29	5	18	35
	Females	27	6	18	35
Stature: (m)	Males	1.81*	0.07	1.64	1.95
	Females	1.61	0.08	1.45	1.79
Body mass: (kg)	Males	82*	7	65	93
	Females	68	9	50	89

Note: * Males significantly different from females ($p<0.05$)

4.3.2 Quadriceps and Hamstring torques at three angular velocities

Maximal concentric Quadriceps and eccentric Hamstring muscle strength (mean ± SD) at three angular velocities (60, 120 and 240°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and knee joint angles (15°, 30° and 45°) are shown for males and females in Table 4.

Table 4 Angle specific torque values (N·m) of concentric quadriceps and eccentric hamstring muscle groups (mean ± SD) at three angular velocities.

Variables	Angle specific torque values at 60°·s^{-1}		Angle specific torque values at 120°·s^{-1}		Angle specific torque values at 240°·s^{-1}	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
Con Q at 15°	74 ± 12	43 ± 10	52 ± 8	42 ± 6	44 ± 9	38 ± 5
Con Q at 30°	123 ± 19	87 ± 15	76 ± 12	57 ± 8	57 ± 8	49 ± 4
Con Q at 45°	211 ± 24	164 ± 19	144 ± 23	117 ± 21	94 ± 15	62 ± 11
Con Q at PT	240 ± 16	200 ± 17	213 ± 19	172 ± 19	154 ± 16	115 ± 11
Ecc H at 15°	58 ± 8	24 ± 5	47 ± 5	29 ± 5	46 ± 4	30 ± 4
Ecc H at 30°	102 ± 12	56 ± 12	71 ± 11	45 ± 4	65 ± 11	47 ± 4
Ecc H at 45°	149 ± 15	91 ± 13	112 ± 15	74 ± 11	95 ± 17	49 ± 11
Ecc H at PT	160 ± 14	106 ± 16	155 ± 19	105 ± 12	139 ± 17	78 ± 10

Note: Con, concentric; Q, quadriceps; Ecc, eccentric; H, hamstring and PT, peak torque.

4.3.3 FH/Q ratio values at three angular velocities

FH/Q ratio values (mean ± SD) at three angular velocities (60, 120 and 240°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and knee joint angles (15°, 30° and 45°) are shown for males and females in Table 5.

Table 5 FH/Q ratio values (mean ± SD) at 60, 120 and 240°·s^{-1} obtained as PT and knee joint angles (15°, 30° and 45°) for males and females.

Variables	FH/Q ratio values at 60°·s^{-1}		FH/Q ratio values at 120°·s^{-1}		FH/Q ratio values at 240°·s^{-1}	
	Male	**Female**	**Male**	**Female**	**Males**	**Females**
FH/Q ratio at 15°	75 ± 11.7	62 ± 13.5	88 ± 8.8	75 ± 13	104 ± 17.7	85 ± 15.1
FH/Q ratio at 30°	80 ± 11.7	72 ± 14.1	94 ± 12.2	85 ± 11.3	109 ± 9.9	98 ± 12.1
FH/Q ratio at 45°	70 ± 7.8	62 ± 10.2	79 ± 13.5	73 ± 12.4	97 ± 4.5	79 ± 5.2
FH/Q ratio PT	66 ± 7.2	59 ± 8.5	73 ± 10.2	65 ± 10.3	87 ± 8.2	68 ± 9.4

4.3.4 Sex differences in the FH/Q ratio

As defined in the methods (section 3.5.1), the FH/Q ratio was calculated by dividing eccentric hamstring by concentric quadriceps torque for both angle at PT and three knee joint angles representative of knee extension.

4.3.4.1 Influence of joint angle on the FH/Q ratio

A significant two-factor joint angle (15º, 30º, 45º and PT) by sex (males; females) interaction associated with the repeated measures ANOVA showed that whereby, across joint angles ($F_{(3,\ 108)} = 4.310$, $P < 0.01$), FH/Q ratio was higher for males than females (Figure 12). Irrespective of sex, significant main effects for joint angle were observed ($F_{(3,\ 108)} = 191.195$, $P < 0.01$), whereby, FH/Q ratio decreased with increasing joint angle. Also significant main effects for sex were observed, whereby, across joint angles, FH/Q ratio was higher in males compared with females.

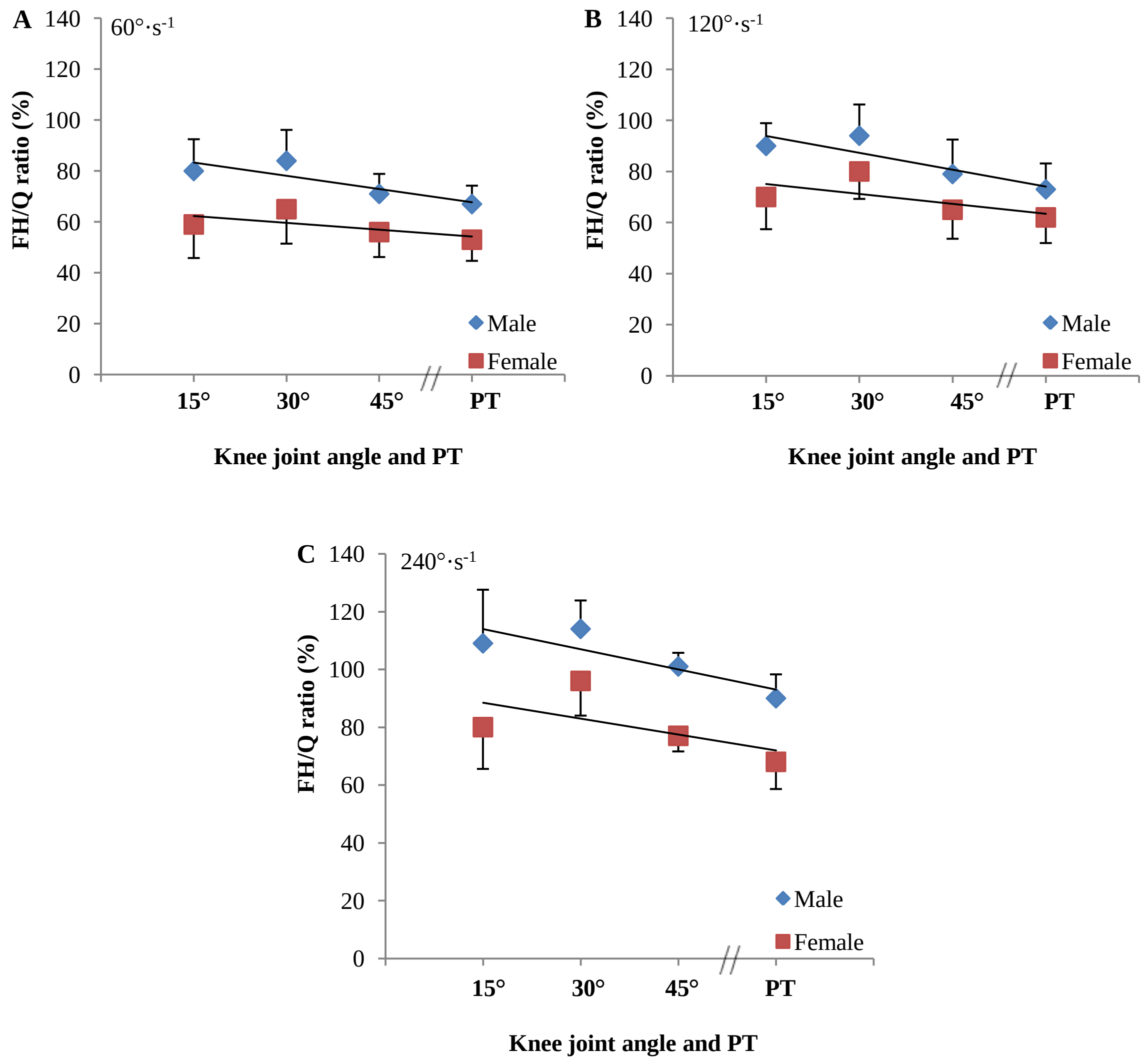


Figure 12 (A, B and C) FH/Q ratios at 60, 120 and 240°·s^{-1} (mean ± SD) across angle (15º, 30º and 45º and PT) for males and females.
Note: There was a significant interaction (p<0.01) between joint angle (15º, 30º, 45º and PT) and sex at 60, 120 and 240°·s^{-1}. Male FH/Q ratio values were significantly (p<0.01) higher than for females and the ratio decreased significantly with increasing angle for males and females.

4.3.4.2 Influence of angular velocity on the FH/Q ratio

A significant two-factor angular velocity (60, 120 and 240°·s^{-1}) by sex (males; females) interaction ($F_{(2, 108)}$ = 13.702, P < 0.01), and angular velocity by knee joint angle interaction ($F_{(6, 108)}$ = 6.244, P < 0.01), associated with the repeated measures ANOVA showed that whereby, across angular velocity, FH/Q ratio was higher for males than females (Figure 13) this interaction also indicated that the FH/Q ratio increases closer to full knee extension with increasing angular velocity. However, there were no significant three-factor interactions ($F_{(2,\ 108)}$ = 1.265, P = 0.261), for angular velocity, joint angle and sex. Significant main effects for angular velocity were observed ($F_{(2,\ 108)}$ = 398.711, P < 0.01), for both males and females, whereby, FH/Q ratio increased with angular velocity. Also significant main effects for sex were observed, whereby, across angular velocity, FH/Q ratio was higher in males than females.

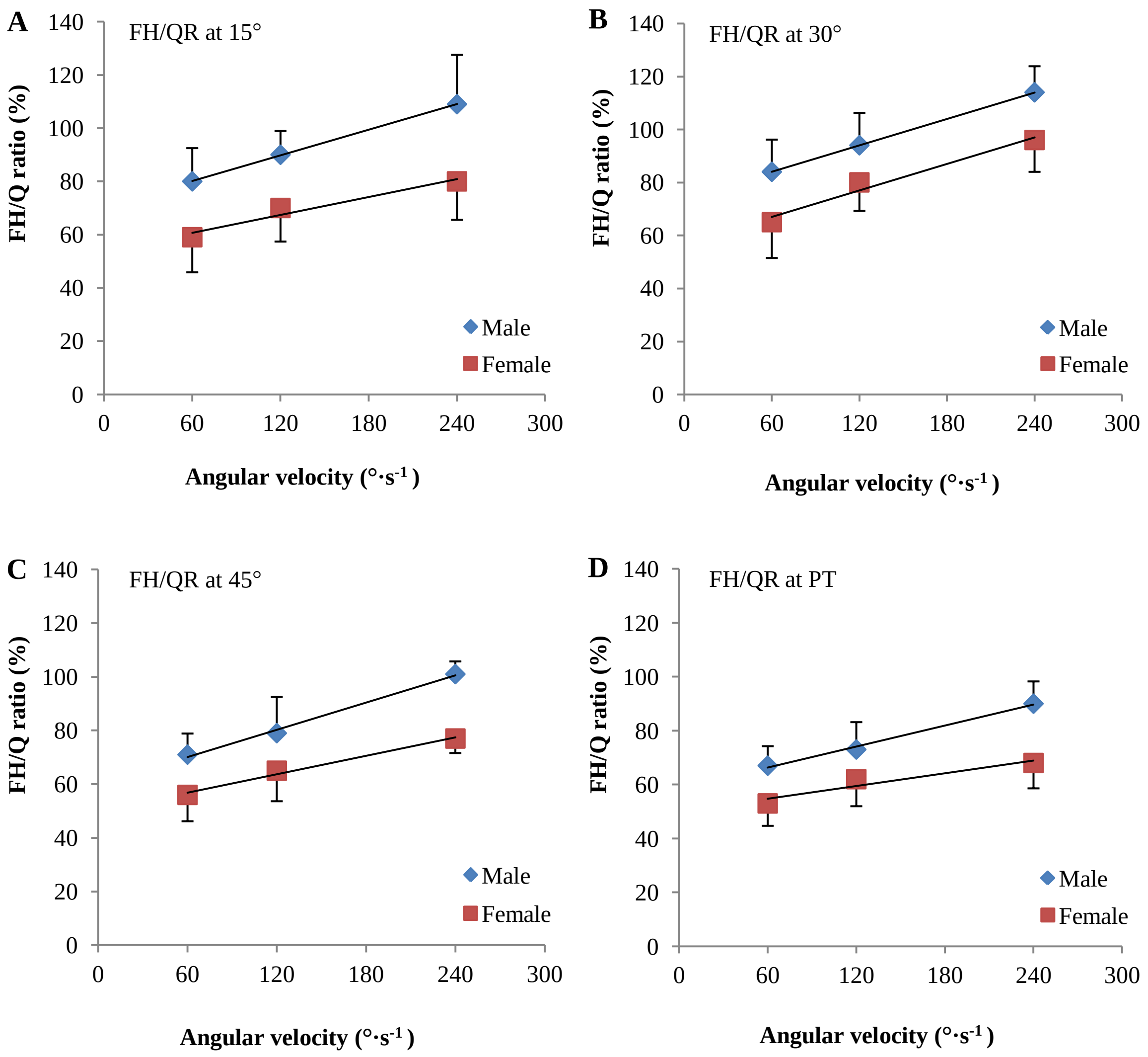


Figure 13 (A, B, C and D) FH/Q ratios of different joint angles (15º, 30º and 45º and PT) at 60, 120 and 240°·s^{-1} (mean ± SD) for males and females.
Note: A significant interaction (p<0.01) between angular velocity and sex. FH/Q ratios at fast angular velocities were significantly (p<0.01) higher than intermediate and slow angular velocities for each knee joint angle.

4.3.5 Summary of results

- Importantly the effect of joint angle was not similar in males and females as statistically significant two-factor interactions between joint angle and sex for the FH/Q ratio were found. The interactions showed a significantly lower FH/Q ratio in females compared to males especially when decreasing joint angle (closer to full knee extension).
- A significant two-factor angular velocity by sex interaction, and angular velocity by knee joint angle interaction, associated with the repeated measures ANOVA showed that the FH/Q ratio was higher in males compared to females with increasing angular velocity and increases closer to full knee extension.
- There was a significantly greater difference between males and females in the FH/Q ratio at the faster angular velocity (240°·s^{-1}) than the difference in the FH/Q ratio at intermediate and low angular velocities (60 and 120°·s^{-1}).

Chapter 5: Study Two

Sex Differences in the Neuromuscular Performance of the Knee Flexor Muscles

5.1 INTRODUCTION

High levels of neuromuscular control are necessary to create dynamic knee stability (Besier et al., 2001). Neuromuscular pre-planning allows feed forward recruitment of the musculature that controls knee joint positioning during landing and pivoting manoeuvres (Besier et al., 2001). Imbalanced or ineffectively timed neuromuscular firing may lead to limb positioning during athletic manoeuvres that puts the ACL under increased strain and risk of injury (Myer et al., 2005b). Co-activation of the hamstrings and quadriceps muscles may protect the knee joint not only against excessive anterior drawer but also against knee abduction and dynamic lower extremity values (Hewett et al., 2008). If the hamstrings are under recruited or weak, quadriceps activation would have to be reduced to provide a net flexor moment required to perform the movement (Hewett et al., 1996, Hewett et al., 2005). Therefore although the ability to generate either maximal torque or angle specific torque is important for dynamic muscular knee stability, the speed at which this torque can be generated is also important. This neuromuscular stability is often overlooked when exploring the dynamic stability of the muscle.

Dynamic muscular control of knee joint alignment, specifically differences in muscle recruitment, firing patterns and strength, may be partly responsible for the sex differences in the incidence of ACL injury. Lower extremity muscle activation during cutting is significantly different between pre-planned and unanticipated conditions; the unanticipated sidestep condition was reported to increase muscle activation in males 10% to 25%, with the greatest increase before initial contact (Besier et al., 2001). Zazulak et al., (2005) reported greater peak rectus femoris activity in female athletes during the pre-contact phase of landing. Increased activation of the rectus femoris in female athletes could be an important neuromuscular contributor to increased ACL strain in women. Increased quadriceps activity combined with low hamstring activation contributes to lowered energy absorption in landing and increased ground reaction forces associated with ACL injury.

Surface EMG enables to examine the signal amplitude and the frequency content associated with skeletal muscle activity. Additionally, when EMG and isokinetic dynamometry are synchronised it is possible to determine electromechanical delay (EMD), which refers to the time lag between the onset of electrical activity and force production (Li and Baum, 2004). EMD has been used in a number of investigations to examine muscle characteristics during shortening and lengthening contractions (Cavanagh and Komi, 1979). Skeletal muscle contraction is associated with a series of neuromechanical events which define the transmission of contractile force to the bony insertion (Blackburn et al., 2009). Electromechanical delay (EMD) has been used classically as a characterization of neuromechanical function (Blackburn et al., 2009). Electromyographic studies demonstrate sex-related differences in the timing of muscle activation during athletic maneuvers (Wojtys et al., 1996a, Rozzi et al., 1999b, Myer et al., 2005a). It has been suggested that females display a longer latency period than males between preparatory and reactive muscle activation (Winter and Brookes, 1991).

Very few studies so far have specifically addressed sex differences in neuromuscular response characteristics. Electromyographical studies have confirmed that females may have sex-related neuromuscular imbalances in muscle contraction patterns proposed to be related to increased risk of ACL injury (Sell et al., 2004, White et al., 2003). White et al.,

(2003) examined sex differences of muscle force and evaluated EMG power spectra of the quadriceps and hamstring muscles between men and women. They determined that the root mean square (RMS) for quadriceps coactivation in women was higher during knee flexion movements which indicate that women are more “quadriceps” dominant making them more susceptible to ACL injury. Winter and Brookes, (1991) have reported that the EMD of the soleus muscle during plantar flexion and elastic charge time were shorter in men than in the women whereas for total reaction time, pre-motor time and force time no sex significant differences were observed. Values of total reaction time, pre-motor time and EMD for women were similar to those reported for men by Viitasalo, and Komi, (1980). Zhou *et al.* (1995) found significantly longer EMD values in 8-12 year-old (61ms for boys; 58ms for girls) 13-16 year-old (44ms for boys; 47ms for girls) and adult (40ms for males; 46ms for females) females compared to males. Longer EMD in females may be as a result of differences in muscle composition; however, current limited evidence suggests that differences in muscle composition are not sufficient to account for the sex differences (Zhou et al., 1995). Therefore differences in muscle activation, such as excitation-contraction coupling and muscle fibre conduction velocity have been implicated in the longer EMD for females.

Huston and Wojtys (1996) reported that female athletes have a slower response of hamstring activation to anterior stress on the ACL. A number of adult studies have suggested that males demonstrate a shorter EMD compared to females and have attributed this to greater musculotendinous stiffness in males (Blackburn et al., 2009, Zhou et al., 1995, Grosset et al., 2009). Only one study appears to have explored sex differences in EMD of the knee extensors during eccentric muscle actions (Blackburn et al., 2009) and reported no significant sex difference. However, musculotendinous stiffness and rate of force production were greater in males; time to produce 50% peak force (time 50%) was shorter in males, and time 50% was negatively correlated with musculotendinous stiffness. These results suggest that neuromechanical hamstring function in females may limit dynamic knee joint stability, potentially contributing to the greater female ACL injury risk. Whether EMD contributes to the greater relative risk of non-contact ACL injury in females is unclear as further research is needed to explore the sex related changes in EMD, especially during eccentric actions of the hamstrings at a range of velocities.

There are a range of issues with the limited data that have explored sex difference in EMD, that include, but are not limited to: a) very small sample sizes; b) differing methods for calculating EMD; c) mainly isometric actions which do not reflect functional performance; d) a limited range of movement velocities have been explored; e) only one study has explored EMD from eccentric actions; and f) there is a lack of data exploring any differences in EMD between the different muscles that comprise the hamstring muscles. Therefore, this study proposes to examine sex differences in the EMD of the hamstrings muscle, conducted at 90° of knee flexion, during eccentric actions, from a range of movement velocities, in a large sample of participants to explore the role that neuromuscular functioning has on knee stability and associated risk of ACL injury.

5-2 METHODS

5-2-1 Participants

The participants of study one were also used in study two (see physical characteristics in Table 3 in chapter 4).

5-2-2 Study design

This study was designed to investigate the neuromuscular functioning of the hamstring muscles during an eccentric action in a non-fatigued state. The eccentric testing of this study started 7 days after familiarisation session and after the concentric quadriceps testing for study one as described in Figure (14).

Baseline measurement	**40 minutes**		
	6-8 min	17 min	15 min
Baseline value of the dominant leg 3 Times for 10s each during the Familiarisation session.	Warm-up	Concentric Quadriceps testing. 3 Reps @ 60°·s^{-1} then 30s rest 3 Reps @ 120°·s^{-1} then 30s rest 3 Reps @ 240°·s^{-1} then 2min rest To change this position	Eccentric Hamstring testing. 3 Reps @ 60°·s^{-1} then 30s rest 3 Reps @ 120°·s^{-1} then 30s rest 3 Reps @ 240°·s^{-1} then 2min rest cool down (Finish all testing)
From prone position	**Cycling**	**From supine position**	**From prone position**

Figure 14: Timeline for data-collection.

5-2-3 Baseline measurement

Prior to any exercise and before warmed up, an active surface EMG electrode configuration was placed over the hamstrings muscles long head parallel to the direction of action potential propagation. Electrode locations were determined via identification of the area of greatest muscle bulk within the muscle belly. Proper electrode placement was verified via manual muscle testing (Hislop and Montgomery, 2002). Baseline values of the dominant leg was taken 3 times (10s each) in the familiarisation session from prone position with hip angle of 0° and fully relaxed. The foot was positioned off the end of the bed (See Figure 15).

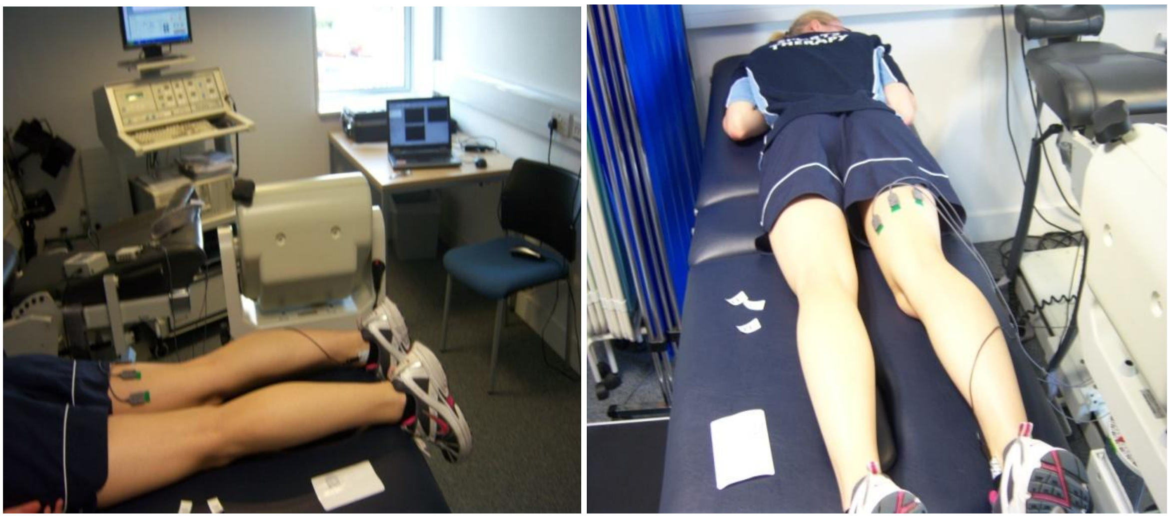


Figure (15) A participant in a prone position, fully relaxed for baseline measurement.

5-2-4 EMG measurement

7 days after the familiarisation session participants returned to the laboratory. Testing were performed during eccentric PT assessments of the hamstring muscles following the application of surface electrodes from prone position on the dominant leg (using the same isokinetic procedures highlighted in general methods section 3-4-2) to obtain EMG data representative of the muscle activity in a pre-fatigue state. The participants were asked to exert maximal voluntary contractions (MVC) as quickly as possible when hearing a specific sound generated by Isokinetic machine. The contraction force was displayed on an analogue device (all EMG measurement procedures highlighted in general methods section 3-4-3). Feedback and encouragements were given to improve consistency during the subsequent testing session.

5-2-5 Data analysis

For this study, analysis was performed for the independent variables of knee angular velocity (60, 120, and 240°·s^{-1}), hamstring muscle (BF, SM, ST), and sex (male and female) using a mixed-factorial (3 x 3 x 2) analysis of variance (ANOVA) to determine the influence on the dependent variable of electromechanical delay (EMD). The three independent variables include two within-subjects factors: knee angular velocity, hamstring muscle, and a between-subjects factor of sex.

Raw EMG data was converted to Root Mean Square (RMS) data within the DelSys Data Analysis Software Package. When processing the raw signal of the amplitude of electrical activity with a root mean square, all data points are converted to a singular polarity (rectified) by squaring them then averaging over a user-defined time interval (Dermaux and Sandra, 1999). The EMG data for each section of the movement was normalised against the maximum EMG RMS amplitude recorded in the same muscle. To investigate the true EMD in a contraction, the maximal electromechanical delay (EMD max) value was determined as the longer EMD of the three muscles. In this case, the signal recorded from the electrodes placed closer to the motor point was used in the comparison (Zhou et al., 1995).

5.3 RESULTS OF STUDY 2

5.3.1 EMD values at three angular velocities

EMD values (mean ± SD of hamstring muscles (BF, SM and ST and Max) at three angular velocities (60, 120 and 240°·s^{-1}) obtained during eccentric actions are shown for males and females in Table 6.

Table 6 Pre-post fatigue EMD values (mean ± SD) of hamstring muscles at 60, 120 and 240°·s^{-1} obtained for males and females.

Variables	EMD values at 60°·s^{-1}		EMD values at 120°·s^{-1}		EMD values at 240°·s^{-1}	
	Male	Female	Male	Female	Males	Females
EMD of BF	24 ± 3.2	27 ± 4.1	40 ± 12	42 ± 13.1	52 ± 8.5	57 ± 9.5
EMD of SM	25 ± 3.6	27 ± 3.9	40 ± 11.9	42 ± 12.6	53 ± 10.8	58 ± 9.5
EMD of ST	25 ± 4	26 ± 4.5	40 ± 14.4	43 ± 12	53 ± 9.6	57 ± 8.6
Max of EMD	27 ± 3.1	29 ± 3.5	47 ± 11.2	51 ± 10.8	59 ± 7.2	63 ± 7.7

5.3.2 Influence of sex and angular velocity on the EMD of hamstring muscles

For the EMD of hamstring muscles, no statistically significant interaction ($F_{(2, 108)} = 0.671$, $P = 0.512$), between angular velocities and sex was observed (Figure 16). However, a significant main effects for angular velocity (60, 120 and 240°·s^{-1}) was demonstrated ($F_{(2, 108)} = 443.177$, $P < 0.01$), indicating an increase in the EMD with increasing angular velocity. For sex differences, the ANOVA analysis indicated that no significant differences were observed in the EMD of the hamstring muscles at three angular velocities.

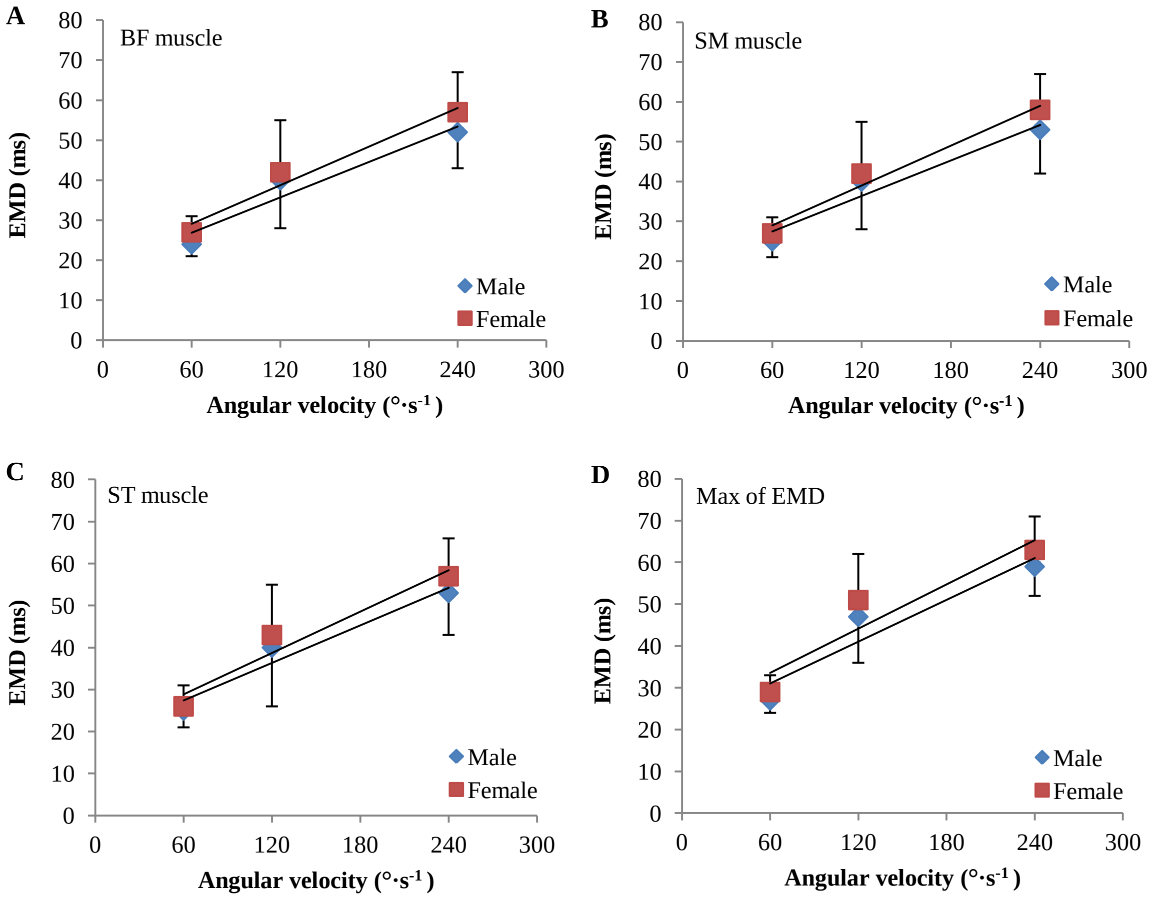


Figure 16 (A, B, C and D) EMD of the hamstring muscles (BF, SM and ST and Max) at 60, 120 and 240°·s^{-1} (mean ± SD) for males and females.
Note: No significant interaction between angular velocities and sex was observed. EMD at fast angular velocities were significantly (p<0.01) slower than intermediate and slow angular velocities for each hamstring muscles.

5.3.3 Influence of hamstring muscles on the EMD across three angular velocities

Repeated measures ANOVA demonstrated that no statistically significant interactions ($F_{(6, 108)}$ = 0.088, P = 0.986), for angular velocity and hamstring muscles (BF, SM and ST and Max) were found in males and females (Figure 17). However a significant main effect for the angular velocity (60, 120 and 240°·s^{-1}) was observed ($F_{(2, 108)}$ = 443.177, P < 0.01) for each hamstring muscle, whereby, EMD increased with increasing angular velocity. No significant main effects for hamstring muscles were observed ($F_{(3, 108)}$ = 0.104, P = 0.901) for both males and females at all three angular velocities.

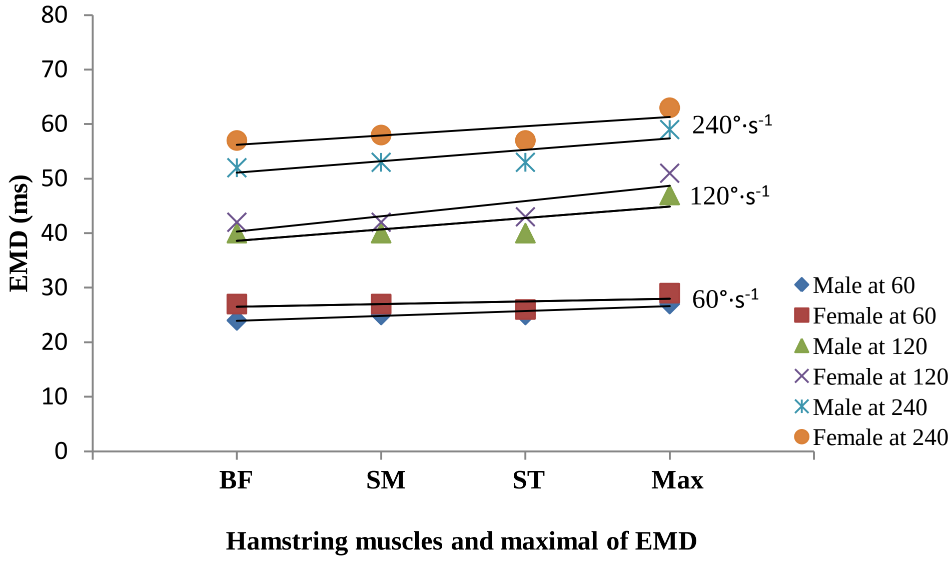


Figure 17 EMD at 60, 120 and 240°·s^{-1} (mean ± SD) across hamstring muscles (BF, SM and ST and Max) for males and females.
Note: No significant interaction for angular velocity and hamstring muscle was observed. EMD at fast angular velocities were significantly ($p<0.01$) higher than intermediate and slow angular velocities for each hamstring muscles.

5.3.4 Summary of results

- Importantly the effect of angular velocity in the EMD was similar in males and females as no statistically significant two-factor interactions between angular velocity and sex for the EMD of Hamstring muscles (BF, SM and ST) were found.
- Also there were no statistically significant interactions, for angular velocity and hamstring muscles (BF, SM and ST and Max) in males and females.
- A significant main effects for angular velocity (60, 120 and 240°·s^{-1}) was demonstrated, indicating an increase in the EMD with increasing angular velocity.
- Irrespective of movement velocity no differences between the EMD of Hamstring muscles groups were found.

Chapter 6: Study three

The Influence of Fatigue on Functional Hamstring to Quadriceps Ratio and Neuromuscular Performance in Males and Females

6-1 INTRODUCTION

With the increased participation of females in sports activities over the past decade, a dramatic increase in the rate of knee injuries involving the anterior cruciate ligament (ACL) has been documented (Marsden et al., 1983, Arendt and Dick, 1995, Oliphant and Drawbert, 1996). The anterior cruciate ligament (ACL) is often injured when athletes execute running and crosscutting manoeuvres during sport activities such as soccer, basketball, and rugby (Zillmer et al., 1992, Arendt and Dick, 1995). Numerous risk factors for non-contact ACL injuries have been identified in the literature (Hughes and Watkins, 2006) and literature focuses on potentially modifiable risk factors related to body positioning, joint loading, and neuromuscular coordination in preventing and reducing the incidence of this injury.

Approximately 70% to 80% of all ACL injuries are non-contact in nature (Moul, 1998, Griffin et al., 2000, Hertel et al., 2004) and, compared with male athletes, female athletes are reportedly 4 to 6 times more likely to sustain a sports-related non-contact ACL injury (Arendt and Dick, 1995). This sex difference in ACL injury rate has led to many studies attempting to elicit physiological, hormonal, and anatomical variances that may predispose females to ACL injury (Loudon et al., 1996, Shelbourne et al., 1998, Wojtys et al., 1998, McLean et al., 1999). Sex differences in neuromuscular control and biomechanical function are thought to be primary factors that may account for this sex bias (Griffin et al., 2000). Irrespective of sex, most injuries occur in the second half of an athletes event when fatigue is commonly present (Hertel et al., 2004). Identifying fatigue as a potential risk factor for an ACL injury may allow for the development of improved prevention strategies.

The presence of fatigue has been theorised to cause dysfunctions in dynamic stability and therefore increase the risk of injury by affecting afferent and efferent systems as well as muscle function itself. The manifestations of functional changes occurring with fatigue are multiple and depend on the joint angle, angular velocity, action type (Green, 1997) and on the training status of participant (Hickner et al., 2001). Eccentric muscle actions possess several unique features which may explain why they are associated with muscle damage and subsequent injury risk (Eston et al., 2003). During concentric actions, work is done by the muscle, but during eccentric action, work is done on the muscle by the external lengthening forces (Eston et al., 2003). During running the extensor muscles of the lower limbs eccentrically contract during each stride to decelerate the centre of mass after the foot touches the ground (Walmsley et al., 1978). Eccentric muscle contraction through downhill running has been associated with increased mechanical stress (Iversen and McMahon, 1992). The vertical impact peak force was reported to be higher during short-term downhill running than during level running (Hamill et al., 1984, Dick and Cavanagh, 1987).

The fatigue produced by any activity can be assessed by comparing the force of maximal voluntary contraction before and after exercise (Rahnama et al., 2003). In the FH/Q ratio if the hamstrings eccentric peak torque is equal to the peak concentric quadriceps torque then the ratio is 1:1 and the joint is supposedly not at risk whereas if the quadriceps are stronger, then the ratio is less than 1, and the joint is considered at risk (Hughes and Watkins, 2006). Consequently, in the fatigued state, the functional hamstring to quadriceps ratio should be less than in the non-fatigued state if it is to be considered that the functional hamstring to quadriceps ratio is a good indicator of the injury risk at the knee. Although fatigue has also been proposed to increase the risk of ACL injury (Hertel et al., 2004), there is currently no evidence to suggest that fatigue has a greater effect on the incidence of ACL injury in females compared with males (Hughes and Watkins, 2006). In addition, most of the literature to date evaluating the effect of fatigue on neuromuscular reflex behaviour has been conducted almost exclusively on males. While few studies have examined the effects of sex on EMD (Bell and Jacobs, 1986, Winter and Brookes, 1991) and found EMD to be longer in females than males, no studies could be found specific to neuromuscular reflex behaviour at the knee as a function of both sex and fatigue.

Previous studies have used active isokinetic dynamometers to elicit eccentric activations by applying force in the opposite direction to the attempted concentric action of the muscle (De Ste Croix et al., 1999). Isokinetic flexion and extension exercises do not simulate the joint forces occurring during activities of sport participation. Therefore, this method of inducing muscular fatigue may effectively create fatigued musculature without replicating the joint forces associated with sport activities such as running, cutting, and jumping, which appear to be necessary to induce alterations in ligament laxity. The length of the activated muscles and the forces exerted during eccentric dynamometry are different compared with other modes of eccentric exercise. In addition, submaximal hamstring fatigue is effectively associated with a mechanical loss of knee stability. This decrease in joint stability may explain at least in part a higher risk of ACL injury, especially in fatigued muscles. Therefore, this potential injury risk might be caused by a decrease in reflex force generation rather than by a moderate increase in latency. Although studies have already found that thigh muscle fatigue leads to larger knee moments (Wikstrom et al., 2004), loss of knee stability (Skinner et al., 1986, Wojtys et al., 1996b) or adverse effects on knee kinematics (Nyland et al., 1994), there is no study with a clear focus on the relationship between neuromuscular control of the hamstrings in terms of reflex components and functional knee stability in fatigued muscles.

Therefore, this study is designed to examine the influence of fatigue on sex differences in FH/Q ratio and the neuromuscular performance of the hamstrings muscle that appear to be associated with reduced knee stability and an increased risk of ACL injury. Where relevant, these interactions will take account of the potential confounding influence of joint angle and angular velocity.

6-2 METHODS

6-2-1 Participants

One hundred healthy males (n=50) and females (n=50) were recruited from the university population (see physical characteristics in Table 7).

6-2-2 Study design

A pilot study was undertaken to examine the proposed fatigue protocol with the participants of the research. This study comprised a partially repeated measures design investigating the FH/Q ratio and neuromuscular functioning of the hamstrings muscles in both a fatigued and non-fatigued state in males and females. The testing for this study started 7 days after familiarisation session as described in Figure (18).

90 minutes			
6-7 min	51 min	17 min	15 min
Warm-up 3min cycling then 3min downhill running	Downhill running 5 Reps × 8min with 2min rest between each bout after that 3min rest To start testing	Concentric Quadriceps testing. 3 Reps @ 60°·s^{-1} then 30s rest 3 Reps @ 120°·s^{-1} then 30s rest 3 Reps @240°·s^{-1} then 2min rest To change this position	Eccentric Hamstring testing. 3 Reps @ 60°·s^{-1} then 30s rest 3 Reps @ 120°·s^{-1} then 30s rest 3 Reps @240°·s^{-1} then 2min rest cool down (Finish all testing)
Cycling/running	**Protocol of fatigue**	**From supine position**	**From prone position**

Figure 18: Timeline for data-collection.

6-2-3 Test session

6-2-3-1 Warm up

The participants warmed up for 3 minutes by cycling at 60 W on a Monark cycle ergometer 814E (Varberg, Sweden).

6-2-3-2 Familiarisation to downhill running

After warming up, the participants were asked to perform 3 minutes downhill running on a motorised treadmill before starting the fatigue protocol to familiarise them with the equipment and with the downhill aspect of running and the speed they would run at. After completing the fatigue protocol, they were asked to perform 3 sub maximal action specific repetitions and 2 maximal repetitions at 120°·s^{-1} prior to the concentric and eccentric tests to familiarise them to the equipment and all testing procedures.

6-2-3-3 Downhill running fatigue protocol

Each participant performed an intermittent downhill run protocol (Figure 19), as used in previous studies (Eston et al., 1995, Eston et al., 1996). This consisted of a 40 min of intermittent bouts of 5 × 8 min on a -10% decline on a Motorised treadmill (ELG. Woodway, Weil am Rhein, Grman), with 2 min standing rest between each bout. The speed of the treadmill was set to elicit 80% of the age-predicted maximum heart rate (220 - age; ACSM, 1991) by using a heart rate monitor (Models Fs3c, Polar, Electro Ov. Kempele, Finland) (Lippincott, 2010). At the end of each 8 min bout, heart rate and treadmill speed were recorded and stored.

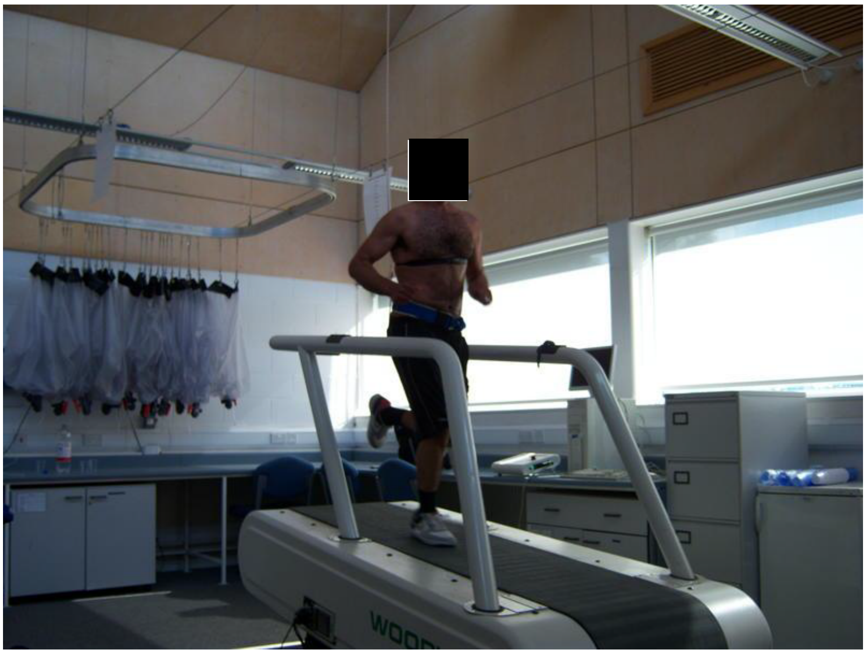


Figure 19: A participant completing the downhill running fatigue protocol.

6-2-3-4 Isokinetic and EMG measurements

Isokinetic and EMG measurements were undertaken as detailed in study 1 and study 2 (all isokinetic and EMG procedures highlighted in general methods section 3-4-2 and 3-4-3).

6-2-3-5 Cool down

Immediately after the testing, participants were invited to complete 2 min cool down on the cycle ergometer at low intensity.

6.2.4 Data analysis

The independent variables of time (pre and post), joint angle (15º, 30º and 45º), angular velocity (60, 180, and 240°·s^{-1}) and sex (male and female) were explored using a mixed-factorial (2 x 3 x 3 x 2) analysis of variance (ANOVA) to determine the influence on dependent variable of the functional ratio. The four independent variables include three within-subjects factors: time, knee joint angle, angular velocity and a between-subjects factor of sex (male and female).

The independent variables of time (pre and post), hamstring muscles (BF, SM, ST), angular velocity (60, 180, and 240°·s^{-1}) and sex (male and female) using a mixed-factorial (2 x 3 x 3 x 2) analysis of variance (ANOVA) to determine the influence on dependent variable of the electromechanical delay. The four independent variables include three within-subjects factors: time, hamstring muscles, angular velocity and a between-subjects factor of sex (male and female).

6.3 RESULTS OF STUDY 3

- **Influence of fatigue on sex differences in FH/Q ratio and EMD of hamstring muscles**

6.3.1 Physical characteristics

The physical characteristics (age, stature, and body mass) of 100 healthy males (n=50) and females (n=50) are presented for each group in Table 7. There were no significant differences between males and females in age but males were significantly ($p<0.05$) taller and had greater body mass.

Table 7 Description of participant physical characteristics of study 3

Variables	Group	Mean	SD	Minimum	Maximum
Age: (y)	Males	29	5	18	35
	Females	27	6	18	35
Stature: (m)	Males	1.82*	0.07	1.67	1.95
	Females	1.61	0.08	1.46	1.79
Body mass: (kg)	Males	82*	7	65	93
	Females	69	9	50	89

Note: * Males significantly different from females ($p<0.05$)

6.3.2 Quadriceps and Hamstring torque pre-post fatigue

6.3.2.1 Quadriceps and Hamstring torque at 60°·s^{-1}

Pre-post fatigue maximal PT concentric Quadriceps and eccentric Hamstring muscle torque (mean ± SD) at slow angular velocity (60°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and at knee joint angles (15°, 30° and 45°) are shown for males and females in Table 8.

Table 8 Pre-post fatigue angle specific PT values (N·m) of concentric quadriceps and eeccentric hamstring muscle groups (mean ± SD) throughout a 90 º ROM at 60°·s^{-1}.

Variables	pre-fatigue angle specific torque values at 60°·s^{-1}		post-fatigue angle specific torque values at 60°·s^{-1}	
	Male	Female	Male	Female
Con Q at 15°	74 ± 12	43 ± 10	56 ± 10	38 ± 4
Con Q at 30°	123 ± 19	88 ± 15	87 ± 9	63 ± 9
Con Q at 45°	211 ± 24	164 ± 19	141 ± 30	111 ± 26
Con Q at PT	240 ± 16	200 ± 17	190 ± 19	166 ± 16
Ecc H at 15°	54 ± 8	26 ± 5	36 ± 5	18 ± 4
Ecc H at 30°	97 ± 12	62 ± 12	63 ± 9	35 ± 4
Ecc H at 45°	146 ± 15	100 ± 13	80 ± 13	44 ± 10
Ecc H at PT	158 ± 14	116 ± 15	97 ± 10	60 ± 11

6.3.2.2 Quadriceps and Hamstring torque at 120°·s^{-1}

Pre-post fatigue maximal PT concentric Quadriceps and eccentric Hamstring muscle torque (mean ± SD) at intermediate angular velocity (120°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and at knee joint angles (15°, 30° and 45°) are shown for males and females in Table 9.

Table 9 Pre-post fatigue angle specific PT values (N·m) of concentric quadriceps and eeccentric hamstring muscle groups (mean ± SD) throughout a 90 º ROM at 120°·s^{-1}.

Variables	pre-fatigue angle specific torque values at 120°·s^{-1}		post-fatigue angle specific torque values at 120°·s^{-1}	
	Male	Female	Male	Female
Con Q at 15°	52 ± 8	42 ± 6	53 ± 8	32 ± 5
Con Q at 30°	76 ± 12	58 ± 8	61± 8	30 ± 9
Con Q at 45°	144 ± 23	117 ± 21	150 ± 27	120 ± 23
Con Q at PT	213 ± 19	172 ± 19	185 ± 19	162 ± 16
Ecc H at 15°	46 ± 5	31 ± 5	43 ± 6	22 ± 5
Ecc H at 30°	71 ± 11	48 ± 4	54 ± 10	24 ± 5
Ecc H at 45°	112 ± 15	84 ± 11	102 ± 13	61 ± 12
Ecc H at PT	155 ± 19	111 ± 12	114 ± 17	75 ± 16

6.3.2.3 Quadriceps and Hamstring torque at 240°·s^{-1}

Pre-post fatigue maximal PT concentric Quadriceps and eccentric Hamstring muscle torque (mean ± SD) at fast angular velocity (240°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and at knee joint angles (15°, 30° and 45°) are shown for males and females in Table 10.

Table 10 Pre-post fatigue angle specific PT values (N·m) of concentric quadriceps and eeccentric hamstring muscle groups (mean ± SD) throughout a 90 ° ROM at 240°·s^{-1}.

Variables	pre-fatigue angle specific torque values at 240°·s^{-1}		post-fatigue angle specific torque values at 240°·s^{-1}	
	Male	Female	Male	Female
Con Q at 15°	44 ± 9	38 ± 5	38 ± 5	30 ± 5
Con Q at 30°	57 ± 8	49 ± 4	60 ± 8	45 ± 5
Con Q at 45°	94 ± 15	63 ± 11	123 ± 17	97 ± 17
Con Q at PT	154 ± 16	115 ± 11	156 ± 16	133 ± 23
Ecc H at 15°	44 ± 4	32 ± 4	35 ± 4	24 ± 4
Ecc H at 30°	62 ± 11	48 ± 4	60 ± 8	42 ± 5
Ecc H at 45°	91 ± 17	50 ± 11	101 ± 12	62 ± 10
Ecc H at PT	134 ± 17	78 ± 10	118 ± 14	74 ± 10

6.3.3 Per-post fatigue FH/Q ratio values and percentage of changes

6.3.3.1 FH/Q ratio values and percentage of changes at 60°·s^{-1}

Pre-post fatigue FH/Q ratio values and percentage of changes (mean ± SD) at slow angular velocity (60°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and knee joint angles (15°, 30° and 45°) are shown for males and females in Table 11.

Table 11 Pre-post fatigue FH/Q ratio values and percentage (mean ± SD) of changes at 60°·s^{-1} obtained as PT and knee joint angles (15°, 30° and 45°) for males and females.

Variables	Pre-fatigue FH/Q ratio values at 60°·s^{-1}		Post-fatigue FH/Q ratio values at 60°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
FH/Q ratio at 15°	75 ± 12	62 ± 14	65 ± 11	46 ± 9	10 ± 17	16 ± 14
FH/Q ratio at 30°	80 ± 12	72 ± 14	74 ± 11	57 ± 10	6 ± 16	15 ± 18
FH/Q ratio at 45°	70 ± 7.8	62 ± 10	59 ± 13	41 ± 9	11 ± 15	21 ± 14
FH/Q ratio PT	66 ± 7.2	59 ± 9	51 ± 6	36 ± 7	15 ± 10	23 ± 9

6.3.3.2 FH/Q ratio values and percentage of changes at 120°·s^{-1}

Pre-post fatigue FH/Q ratio values and percentage (mean ± SD) of changes at slow angular velocity (120°·s^{-1}) obtained during isokinetic knee extension and flexion as PT and knee joint angles (15°, 30° and 45°) are shown for males and females in Table 12.

Table 12 Pre-post fatigue FH/Q ratio values and percentage (mean ± SD) of changes at 120°·s^{-1} obtained as PT and knee joint angles (15°, 30° and 45°) for males and females.

Variables	Pre-fatigue FH/Q ratio values at 120°·s^{-1}		Post-fatigue FH/Q ratio values at 120°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
FH/Q ratio at 15°	88 ± 9	75 ± 13	82 ± 14	67 ± 10	6 ± 16	8 ± 16
FH/Q ratio at 30°	94 ± 12	86 ± 11	88 ± 10	81 ± 16	6 ± 17	5 ± 20
FH/Q ratio at 45°	79 ± 14	73 ± 12	70 ± 14	52 ± 13	9 ± 20	24 ± 20
FH/Q ratio PT	73 ± 10	65 ± 10	62 ± 11	47 ± 12	11 ± 16	18 ± 15

6.3.3.3 FH/Q ratio values and percentage of changes at 240°·s^{-1}

Pre-post fatigue FH/Q ratio values and percentage (mean ± SD) of changes at slow angular velocity (240°·s-1) obtained during isokinetic knee extension and flexion as PT and knee joint angles (15°, 30° and 45°) are shown for males and females in Table 13.

Table 13 Pre-post fatigue FH/Q ratio values and percentage (mean ± SD) of changes at 240°·s^{-1} obtained as PT and knee joint angles (15°, 30° and 45°) for males and females.

Variables	Pre-fatigue FH/Q ratio values at 240°·s^{-1}		Post-fatigue FH/Q ratio values at 240°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
FH/Q ratio at 15°	104 ± 18	86 ± 15	94 ± 12	82 ± 17	9 ± 23	4 ± 25
FH/Q ratio at 30°	109 ± 10	98 ± 12	100 ± 13	94 ± 11	9 ± 18	4 ± 17
FH/Q ratio at 45°	97 ± 5	79 ± 5	83 ± 12	66 ± 13	14 ± 13	13 ± 14
FH/Q ratio PT	87 ± 8	68 ± 9	76 ± 11	58 ± 11	11 ± 13	10 ± 13

6.3.4 Influence of fatigue on sex differences in the FH/Q ratio

As defined in the methods (section 3.5.1), the FH/Q ratio was calculated by dividing eccentric hamstring by concentric quadriceps muscle strength for both PT and knee joint angles representative of knee extension.

6.3.4.1 Influence of fatigue on sex differences in the FH/Q ratio at 60°·s^{-1}

The results in Figure 18 indicate that a significant three-factor interaction between sex, joint angle and time ($F_{(3, 98)} = 3.590$, $P < 0.05$) for the FH/Q ratio were found. The interactions showed a significantly lower FH/Q ratio in females compared to males when fatigue is present and higher when decreasing joint angle (closer to full knee extension). Additionally, significant main effects for time ($F_{(1, 98)} = 672.431$, $P < 0.01$) were demonstrated, indicating the FH/Q ratio at 60°·s^{-1} was lower post-fatigue compared to pre-fatigue and there was greater difference between males and females in the FH/Q ratio post-fatigue than there was in pre-fatigue. For sex differences, the ANOVA analysis indicated a significant main effect demonstrating a higher FH/Q ratio in males compared to females.

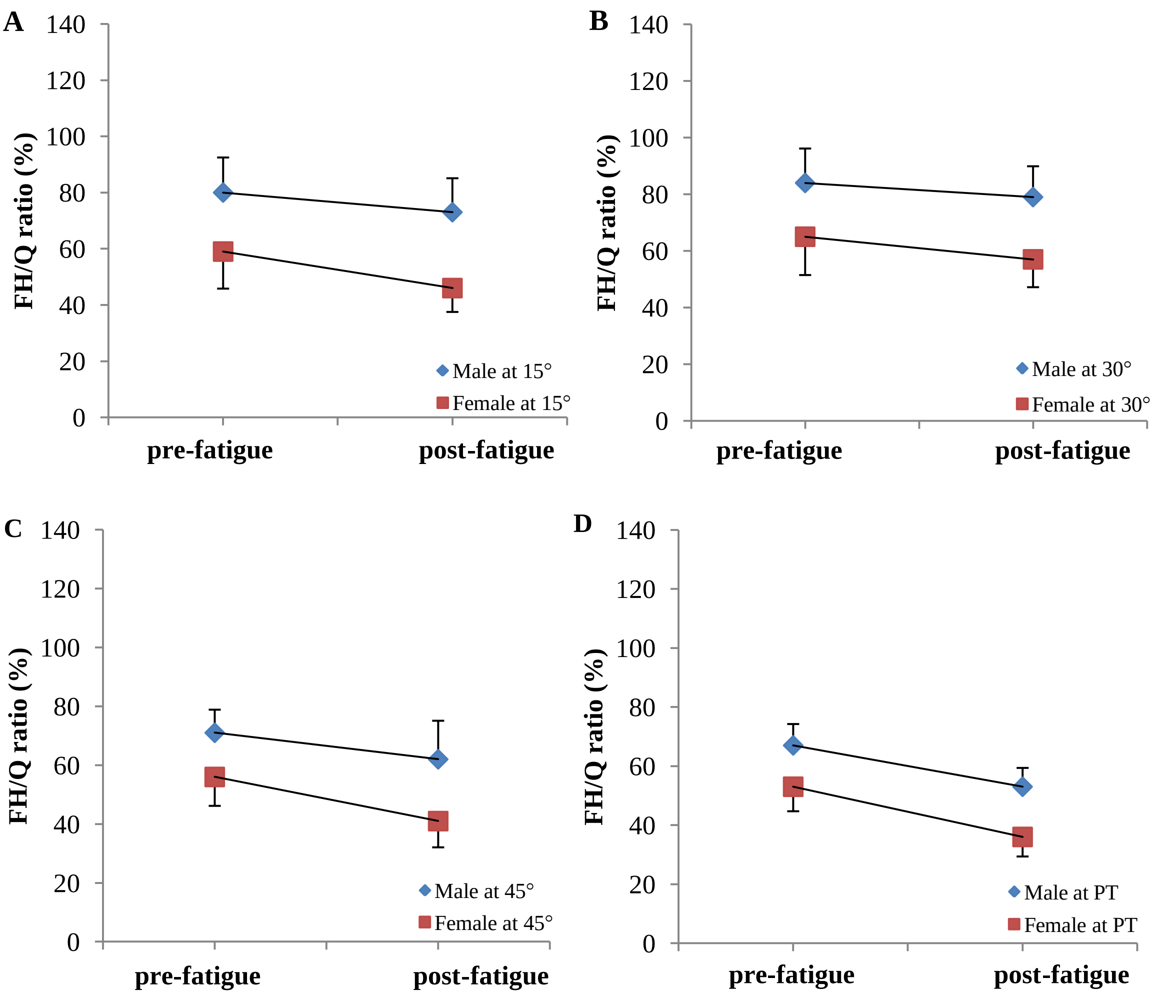


Figure 18 (A, B, C and D) FH/Q ratio (pre-post fatigue) at different joint angle and PT at 60°·s^{-1} (mean ± SD) for males and females.
Note: A significant ($p<0.05$) interaction (sex × joint angle × time ‹pre-post›) for the FH/Q ratio was observed. Significant ($p<0.01$) main effects for the time was observed. Significant main effect for sex was also observed.

6.3.4.2 Influence of fatigue on sex differences in the FH/Q ratio at 120°·s^{-1}

A significant three-factor interaction between sex, joint angle and time ($F_{(3, 98)} = 3.590$, $P < 0.05$) for the FH/Q ratio were found (Figure 19). The interactions showed a significantly lower FH/Q ratio in females compared to males when fatigue is present and higher when decreasing joint angle (closer to full knee extension). Additionally, significant main effects for time ($F_{(1, 98)} = 672.431$, $P < 0.01$) were demonstrated, indicating the FH/Q ratio at 120°·s-1 was lower post-fatigue compared to pre-fatigue and there was greater difference between males and females in the FH/Q ratio post-fatigue than there was in pre-fatigue. For sex differences, the ANOVA analysis indicated a significant main effect demonstrating a higher FH/Q ratio in males compared to females.

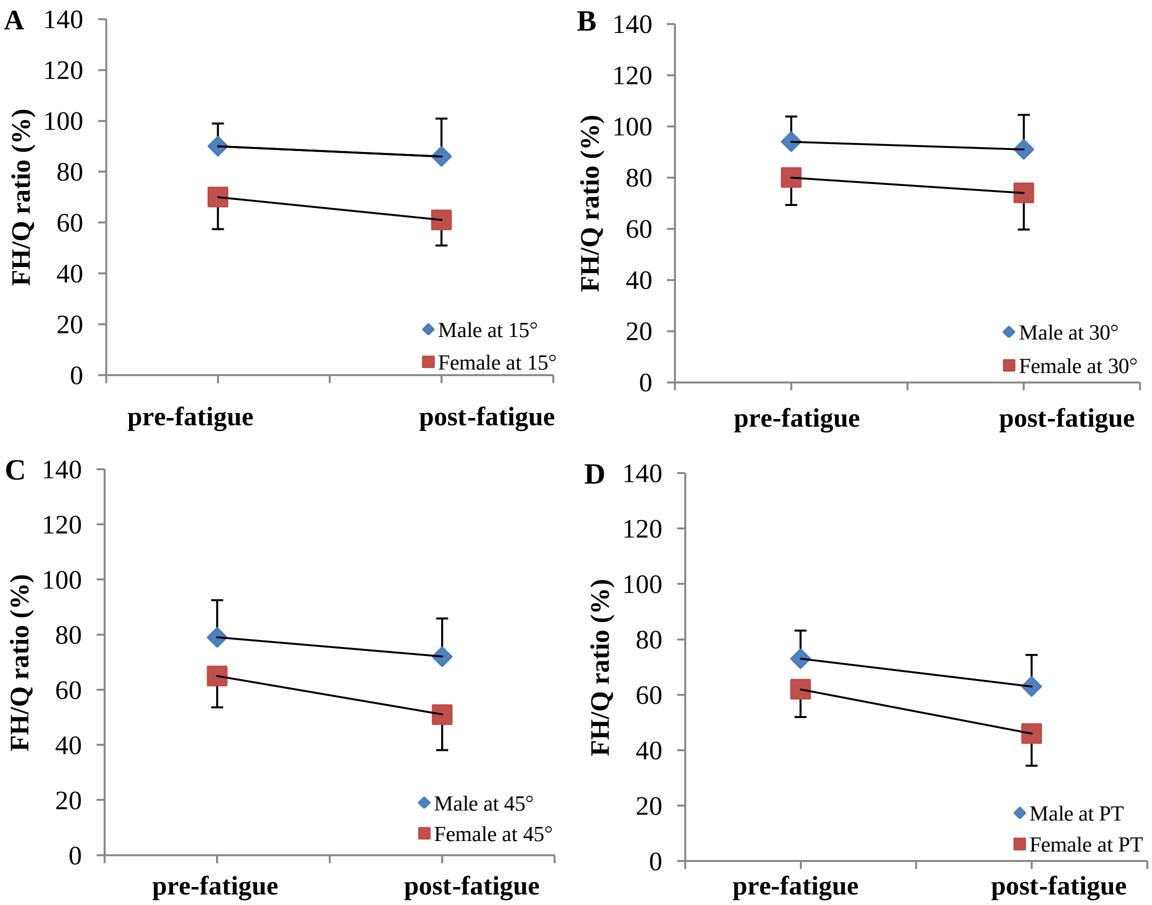


Figure 19 (A, B, C and D) FH/Q ratio (pre-post fatigue) at different joint angle and PT at 120°·s^{-1} (mean ± SD) for males and females.
Note: A significant interaction (sex × joint angle × time ‹pre-post›) for the FH/Q ratio was observed. Significant (p<0.01) main effects for the time was observed. Significant main effects for sex was also observed.

6.3.4.3 Influence of fatigue on sex differences in the FH/Q ratio at 240°·s^{-1}

A significant three-factor interaction between sex, joint angle and time ($F_{(3, 98)} = 3.590$, $P < 0.05$) for the FH/Q ratio were found (Figure 20). The interactions showed a significantly lower FH/Q ratio in females compared to males when fatigue is present and higher when decreasing joint angle (closer to full knee extension). Additionally, significant main effects for time ($F_{(1, 98)} = 672.431$, $P < 0.01$) were demonstrated, indicating the FH/Q ratio at 240°·s-1 was lower post-fatigue compared to pre-fatigue and there was greater difference between males and females in the FH/Q ratio post-fatigue than there was in pre-fatigue. For sex differences, the ANOVA analysis indicated a significant main effect demonstrating a higher FH/Q ratio in males compared to females.

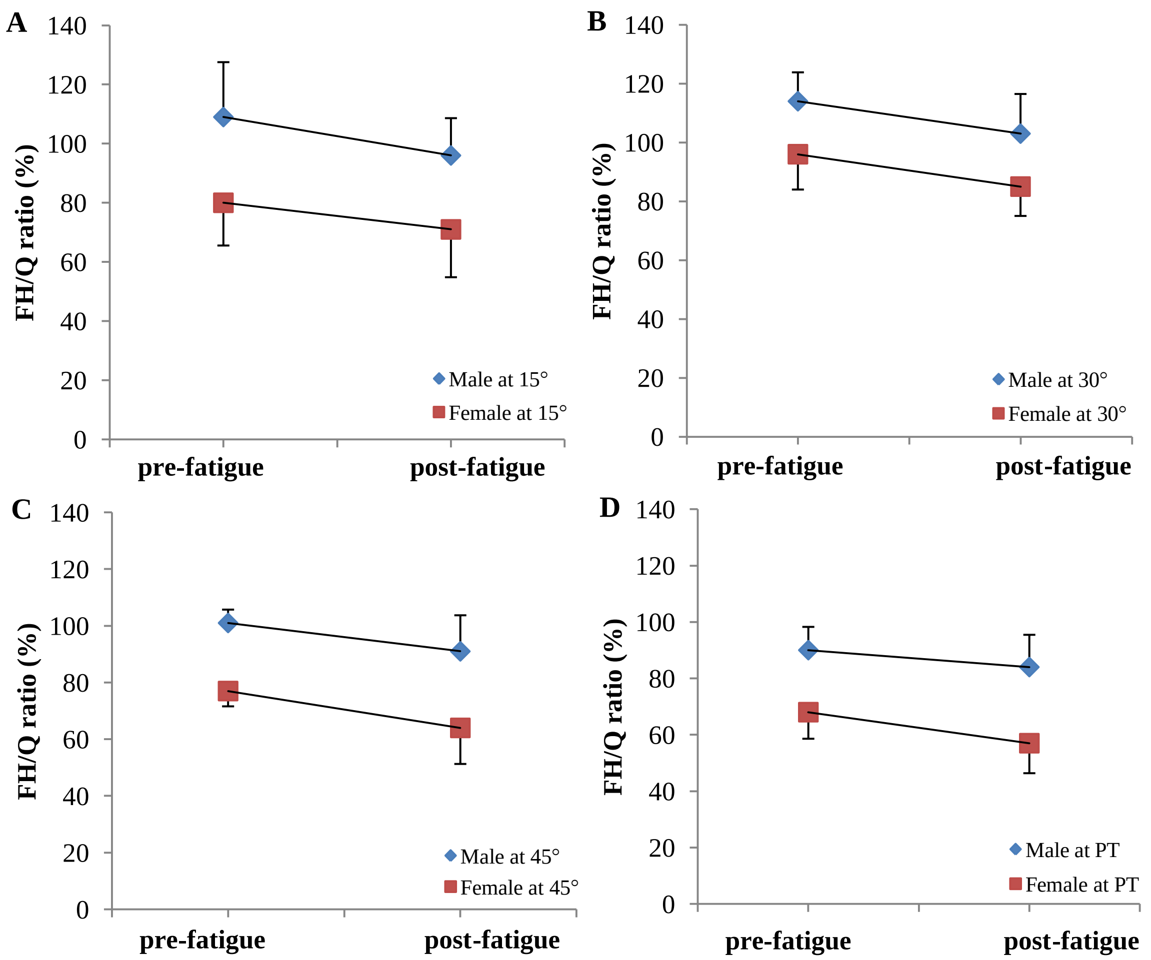


Figure 20 (A, B, C and D) FH/Q ratio (pre-post fatigue) at different joint angle and PT at 240°·s^{-1} (mean ± SD) for males and females.
Note: a significant interaction (sex × joint angle × time ‹pre-post›) for the FH/Q ratio was observed. Significant (p<0.01) main effects for the time was observed. Significant main effects for sex was also observed.

6.3.4.4 Influence of fatigue on the FH/Q ratio of males at three angular velocities

A statistically significant two-factor interaction between angular velocities and time ($F_{(2, 98)}$ = 10.260, P < 0.01) for the FH/Q ratio of males was observed (Figure 21). The interaction showed an increase in the FH/Q ratio with increasing angular velocity especially when fatigue is present. Also a significant main effect for time was demonstrated ($F_{(1, 98)}$ = 672.431, P < 0.01), indicating the FH/Q ratio of males was higher pre-fatigue compared to post-fatigue. Additionally, significant main effects for angular velocity was demonstrated ($F_{(2, 98)}$ = 974.729, P < 0.01), indicating an increase in the FH/Q ratio of males with increasing angular velocity (60, 120 and 240°·s^{-1}).

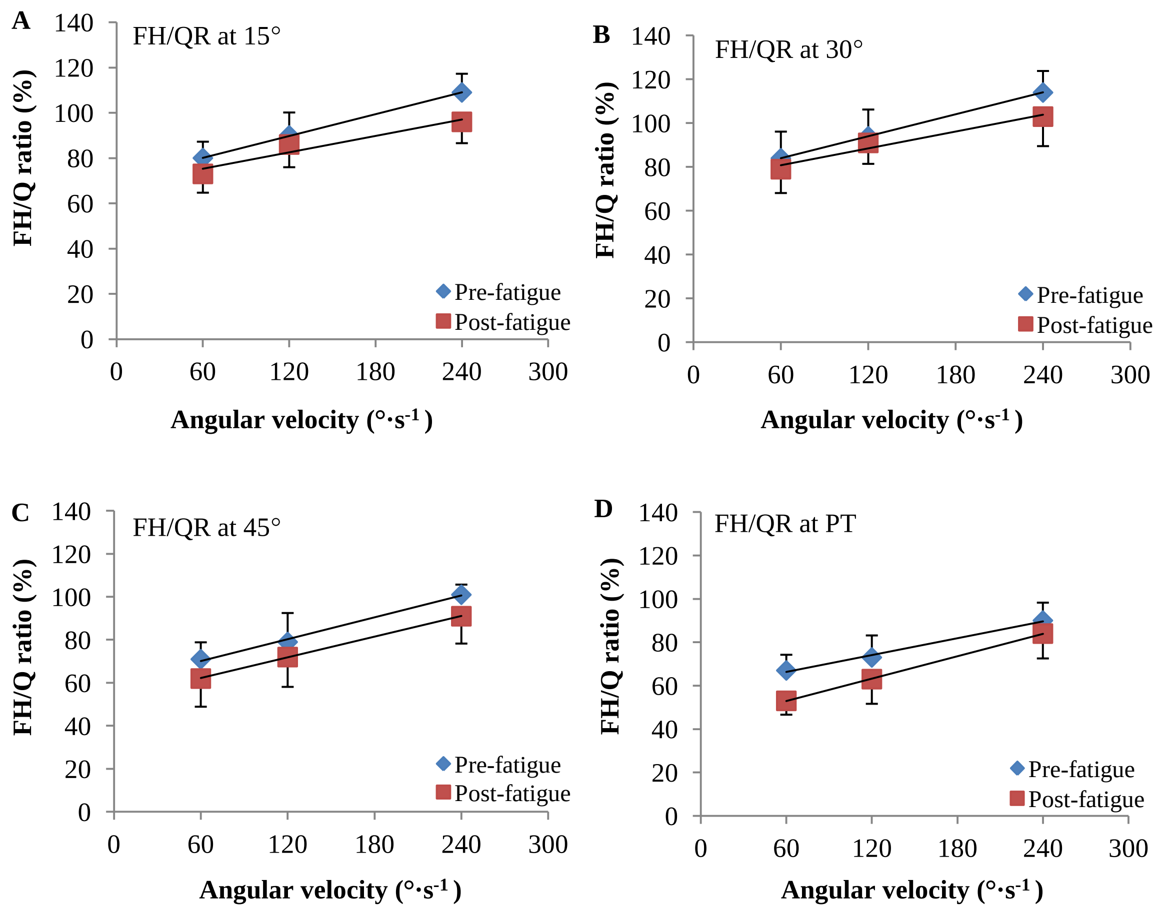


Figure 21 (A, B, C and D) FH/Q ratios at different joint angle (15º, 30º, 45º and PT) at 60, 120 and 240°·s^{-1} (mean ± SD) for males pre-post fatigue.
Note: A significant interaction (angular velocity × time ‹pre-post›) for the FH/Q ratio of males was observed. A significant main effects for the time and angular velocities was observed with higher FH/Q ratio of males in pre-fatigue compared to post-fatigue.

6.3.4.5 Influence of fatigue on the FH/Q of female at three angular velocities

A statistically significant two-factor interaction between angular velocities and time ($F_{(2, 98)}$ = 10.260, P < 0.01) for the FH/Q ratio of females was observed (Figure 22). The interaction showed an increase in the FH/Q ratio with increasing angular velocity especially when fatigue is present. Also a significant main effect for time was demonstrated ($F_{(1, 98)}$ = 672.431, P < 0.01), indicating the FH/Q ratio of females was higher pre-fatigue compared to post-fatigue. Additionally, significant main effects for angular velocity was demonstrated ($F_{(2, 98)}$ = 974.729, P < 0.01), indicating an increase in the FH/Q ratio of females with increasing angular velocity (60, 120 and 240°·s^{-1}).

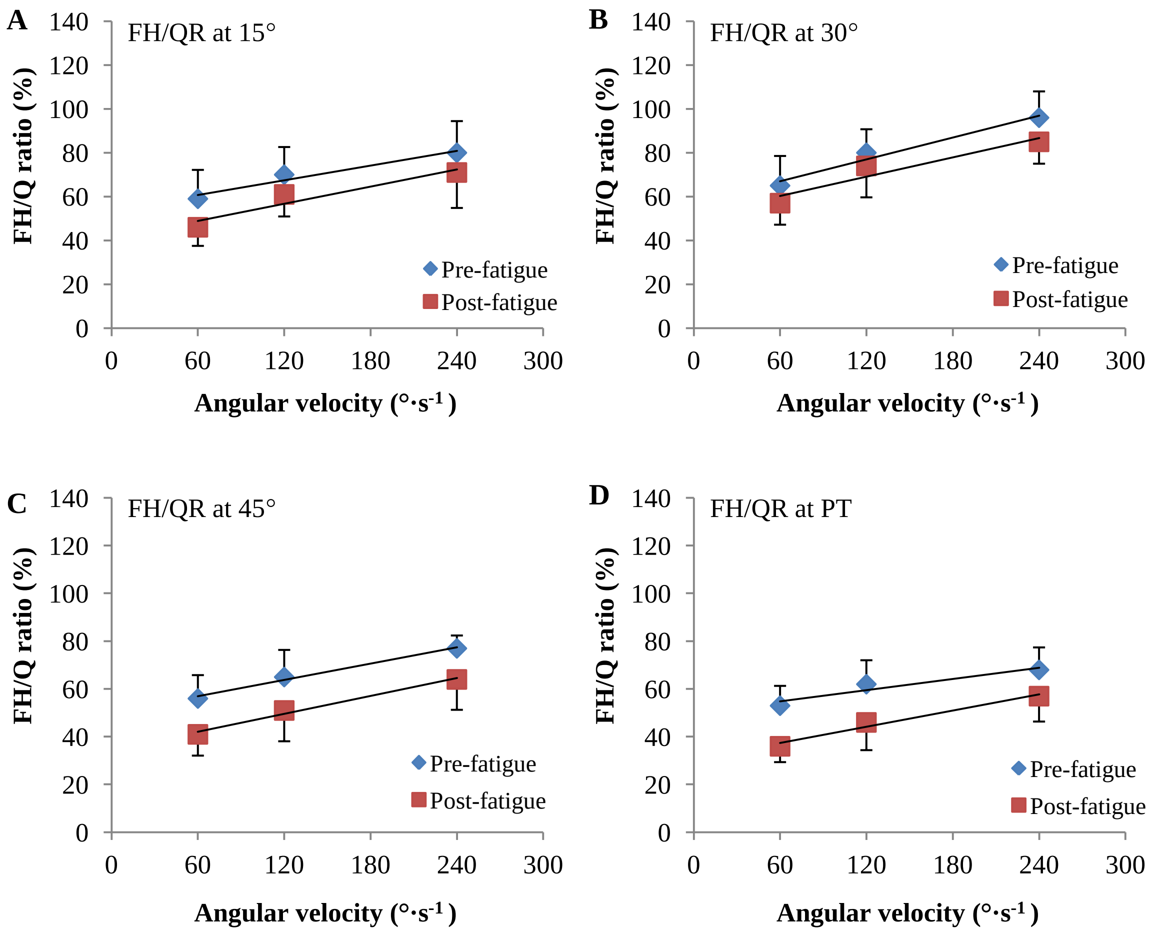


Figure 22 (A, B, C and D) FH/Q ratios at different joint angle (15º, 30º, 45º and PT) at 60, 120 and 240°·s^{-1} (mean ± SD) for females pre-post fatigue.

Note: A significant interaction (angular velocity × time ‹pre-post›) for the FH/Q ratio of males was observed. A significant main effects for the time and angular velocities was observed with higher FH/Q ratio of males in pre-fatigue compared to post-fatigue.

6.3.4.6 FH/Q ratio of male and influence of fatigue on joint angle and PT

A statistically significant two-factor interaction between joint angle and time ($F_{(3, 98)}$ = 5.592, $P < 0.01$) for the functional H/Q ratio of males was observed (Figure 23). The interactions showed a significantly lower FH/Q ratio in males when fatigue is present and decreasing joint angle (closer to full knee extension). Also a significant main effect for joint angle was demonstrated ($F_{(3, 98)}$ = 468.466, $P < 0.01$), indicating the functional H/Q ratio of males was higher pre-fatigue compared to post-fatigue and the functional H/Q ratio was decreased with increasing joint angle.

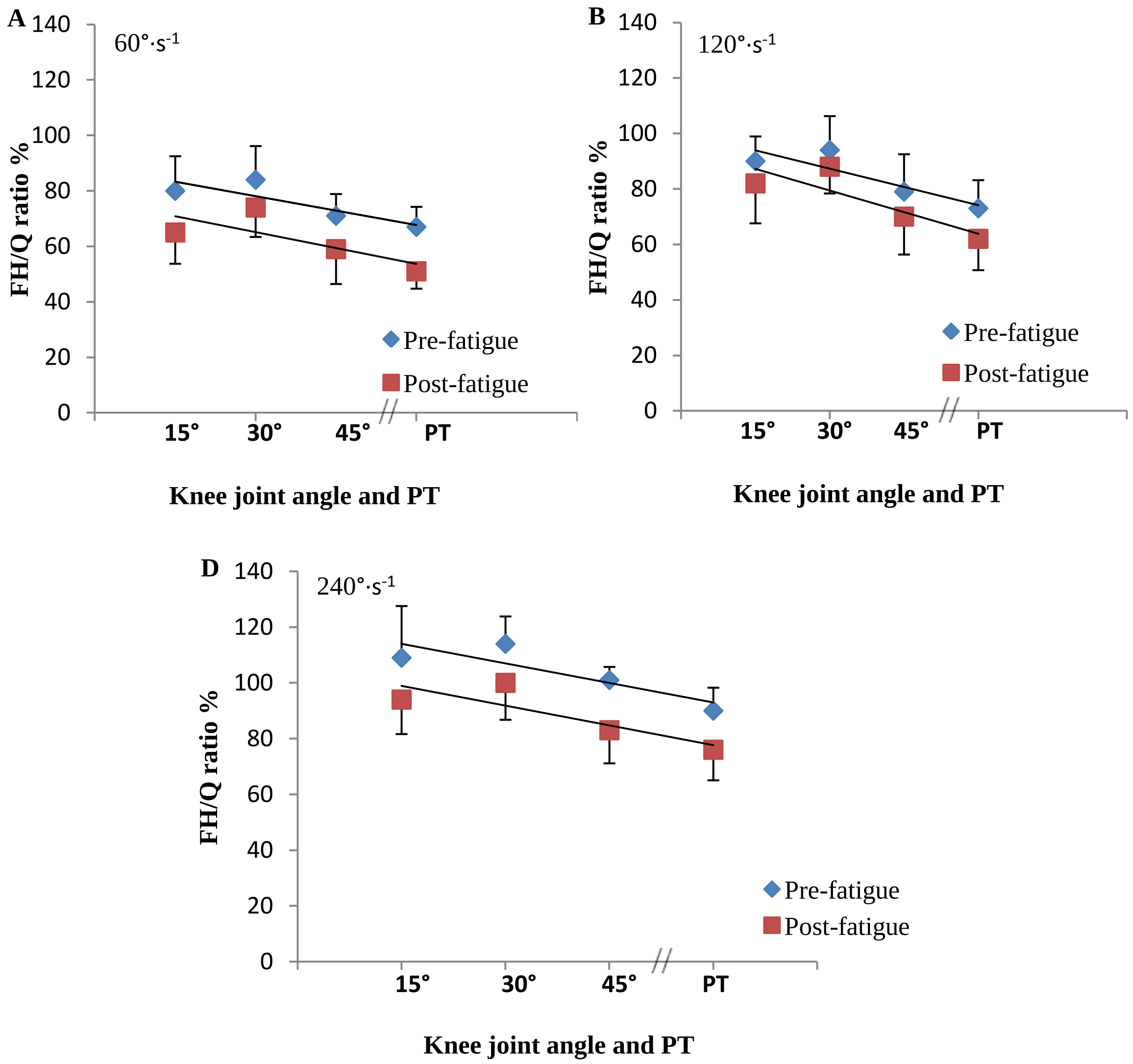


Figure 23 (A, B and D) FH/Q ratios 60, 120 and 240°·s^{-1} (mean ± SD) across joint angle (15º, 30º, 45º and PT) for males pre-post fatigue.
Note: Significant interaction (time ‹pre-post› × joint angle) for the FH/Q ratio of males was observed. Significant main effects for joint angle was observed, indicating the FH/Q ratio of males

was higher in pre-fatigue compared to post-fatigue and the FH/Q ratio was decreased with increasing joint angle.

6.3.4.7 FH/Q ratio of female and influence of fatigue on joint angle and PT

A statistically significant two-factor interaction between joint angle and time ($F_{(3, 98)}$ = 5.592, $P < 0.01$) for the functional H/Q ratio of females was observed (Figure 24). The interactions showed a significantly lower FH/Q ratio in females when fatigue is present and decreasing joint angle (closer to full knee extension). Also a significant main effect for joint angle was demonstrated ($F_{(3, 98)}$ = 468.466, $P < 0.01$), indicating the functional H/Q ratio of males was higher pre-fatigue compared to post-fatigue and the functional H/Q ratio was decreased with increasing joint angle.

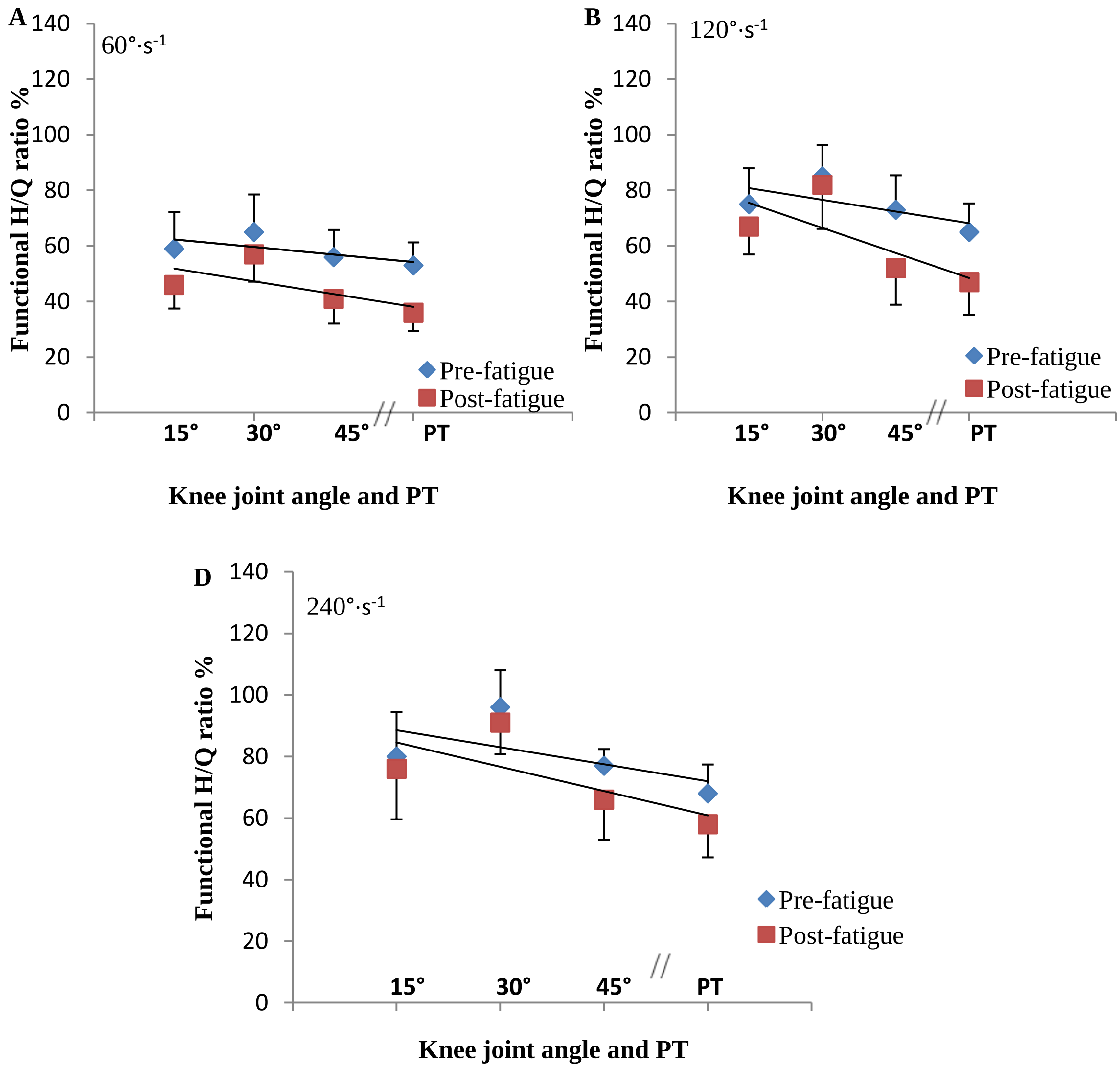


Figure 24 (A, B and D) FH/Q ratios 60, 120 and 240°·s^{-1} (mean ± SD) across joint angle (15º, 30º, 45º and PT) for females pre-post fatigue.
Note: Significant interaction (time ‹pre-post› × joint angle) for the FH/Q ratio of females was observed. Significant main effects for joint angle was observed, indicating the FH/Q ratio of females was higher in pre-fatigue compared to post-fatigue and the FH/Q ratio was decreased with increasing joint angle.

6.3.5 Per-post fatigue EMD values and percentage of changes

6.3.5.1 EMD values and percentage of changes at 60°·s^{-1}

Pre-post fatigue EMD values and percentage of changes (mean ± SD) of hamstring muscles (BF, SM and ST and Max) at slow angular velocity (60°·s^{-1}) obtained during eccentric actions are shown for males and females in Table 14.

Table 14 Pre-post fatigue EMD values and percentage (mean ± SD) of changes of hamstring muscles at 60°·s^{-1} obtained for males and females.

Variables	Pre-fatigue EMD values at 60°·s^{-1}		Post-fatigue EMD values at 60°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
EMD of BF	24 ± 3	27 ± 4	33 ± 10	44 ± 13	9 ± 12	17 ± 10
EMD of SM	25 ± 4	27 ± 4	33 ± 10	44 ± 13	8 ± 12	17 ± 10
EMD of ST	25 ± 4	26 ± 5	34 ± 13	44 ± 12	9 ± 13	18 ± 10
Max of EMD	27 ± 3	29 ± 4	39 ± 11	52 ± 11	12 ± 7	23 ± 8

6.3.5.1 EMD values and percentage of changes at 120°·s^{-1}

Pre-post fatigue EMD values and percentage of changes (mean ± SD) of hamstring muscles (BF, SM and ST and Max) at slow angular velocity (120°·s^{-1}) obtained during eccentric actions are shown for males and females in Table 15.

Table 15 Pre-post fatigue EMD values and percentage of changes (mean ± SD) of hamstring muscles at 120°·s^{-1} obtained for males and females.

Variables	Pre-fatigue EMD values at 120°·s^{-1}		Post-fatigue EMD values at 120°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
EMD of BF	40 ± 12	42 ± 13	52 ± 13	61 ± 13	12 ± 19	19 ± 18
EMD of SM	40 ± 12	42 ± 13	52 ± 12	63 ± 15	12 ± 15	21 ± 18
EMD of ST	40 ± 14	43 ± 12	52 ± 13	63 ± 12	12 ± 21	20 ± 19
Max of EMD	47 ± 11	51 ± 11	59 ± 12	69 ± 13	12 ± 18	18 ± 17

6.3.5.1 EMD values and percentage of changes at 240°·s^{-1}

Pre-post fatigue EMD values and percentage of changes (mean ± SD) of hamstring muscles (BF, SM and ST and Max) at slow angular velocity (240°·s^{-1}) obtained during eccentric actions are shown for males and females in Table 16.

Table 16 Pre-post fatigue EMD values and percentage of changes (mean ± SD) of hamstring muscles at 240°·s^{-1} obtained for males and females.

Variables	Pre-fatigue EMD values at 240°·s^{-1}		Post-fatigue EMD values at 240°·s^{-1}		Percentage of changes post fatigue (%)	
	Male	Female	Male	Female	Males	Females
EMD of BF	52 ± 9	57 ± 10	74 ± 11	85 ± 10	22 ± 14	28 ± 18
EMD of SM	53 ± 11	58 ± 10	74 ± 12	84 ± 9	21 ± 18	26 ± 14
EMD of ST	53 ± 10	57 ± 9	74 ± 11	85 ± 9	21 ± 16	28 ± 14
Max of EMD	59 ± 7	63 ± 8	81 ± 9	90 ± 7	22 ± 13	27 ± 12

6.3.6 Influence of fatigue on Sex differences in the EMD

6.3.6.1 Sex differences in the EMD of hamstring muscles (pre-post) at 60°·s^{-1}

The ANOVA analysis indicated no significant three-factor interaction between sex, hamstring muscle group and time ($F_{(3, 98)} = 0.299$, $P = 0.742$) for EMD (Figure 25). However, statistically significant two-factor interaction between sex and time ($F_{(3, 98)} = 28.738$, $P < 0.01$) for EMD were observed. The interactions showed a significantly longer EMD in females compared to males when fatigue is present. Additionally, significant main effects for time were demonstrated ($F_{(1, 98)} = 709.406$, $P < 0.01$), indicating the EMD of hamstring muscles at 60°·s^{-1} was longer post-fatigue compared to pre-fatigue. For sex differences, the ANOVA analysis indicated that a statistically significant longer EMD post- fatigue at 60°·s^{-1} were observed in females compared to males.

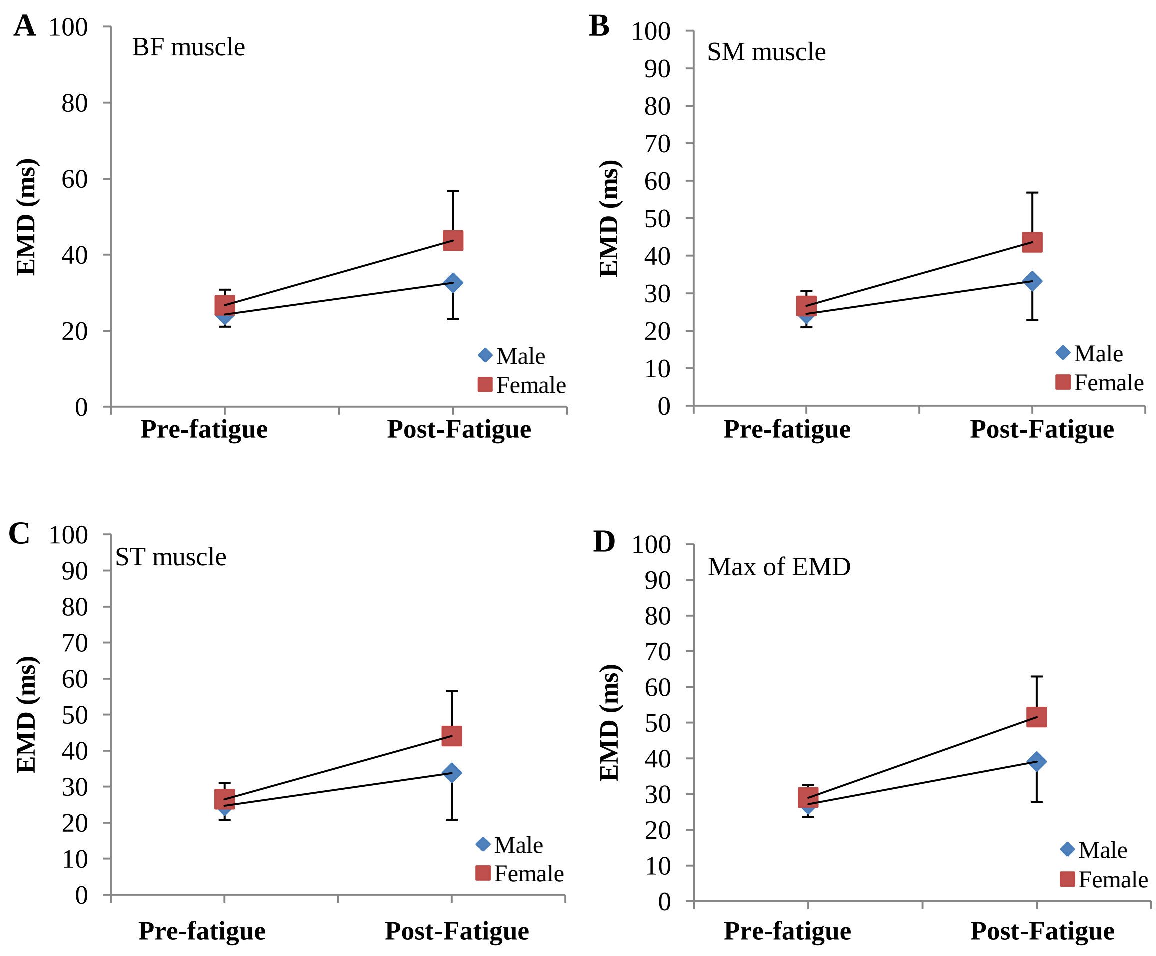


Figure 25 (A, B, C and D) EMD of hamstring muscles (BF, SM and ST and Max) at $60°\cdot s^{-1}$ (mean ± SD) for males and females (pre-post fatigue).
Note: No significant interactions (sex × hamstring muscle groups × time) for the EMD were observed. Statistically significant interactions (sex × time) for the EMD were observed. Significant main effects for the time were observed. Statistically significant longer EMD post- fatigue were observed in females compared to males.

6.3.6.2 Sex differences in the EMD of hamstring muscles (pre-post) at $120°\cdot s^{-1}$

The ANOVA analysis indicated no significant three-factor interaction between sex, hamstring muscle group and time ($F_{(3, 98)} = 0.299$, $P = 0.742$) for EMD (Figure 26). However, statistically significant two-factor interaction between sex and time ($F_{(1, 98)} = 28.738$, $P < 0.01$) for EMD were observed. The interactions showed a significantly longer EMD in females compared to males when fatigue is present. Additionally, significant main effects for time were demonstrated ($F_{(1, 98)} = 709.406$, $P < 0.01$), indicating the EMD of hamstring muscles at 120°·s^{-1} was longer post-fatigue compared to pre-fatigue. For sex differences, the ANOVA analysis indicated that a statistically significant longer EMD post- fatigue at 120°·s^{-1} were observed in females compared to males.

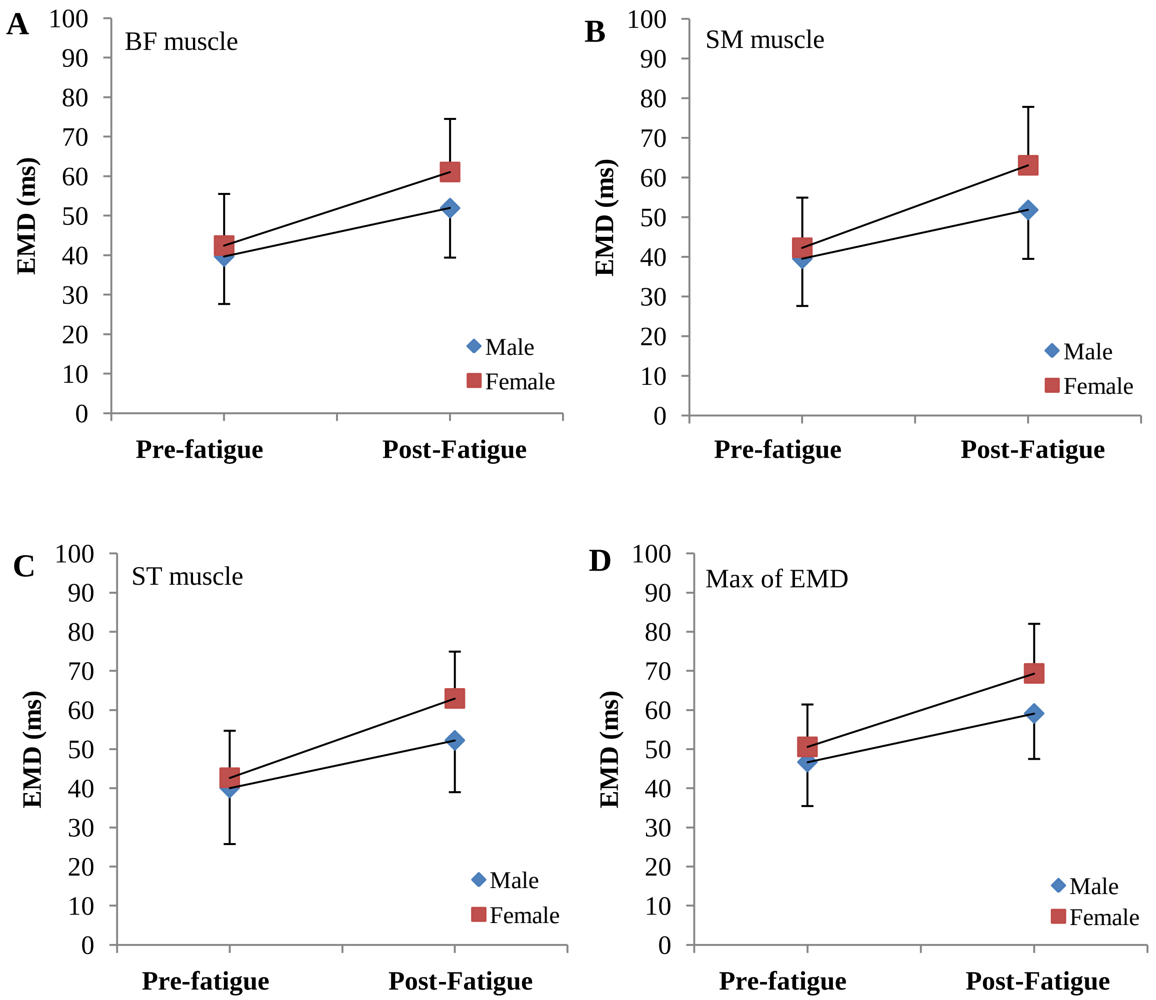


Figure 26 (A, B, C and D) EMD of hamstring muscles (BF, SM and ST and Max) at 120°·s^{-1} (mean ± SD) for males and females (pre-post fatigue).
Note: No significant interactions (sex × Hamstring muscle groups × time) for the EMD were observed. Statistically significant interactions (sex × time) for the EMD were observed. Significant main effects for the time were observed. Statistically significant longer EMD post- fatigue were observed in females compared to males.

6.3.6.3 Sex differences in the EMD of hamstring muscles (pre-post) at 240°·s^{-1}

The ANOVA analysis indicated no significant three-factor interaction between sex, hamstring muscle group and time ($F_{(3, 98)}$ = 0.299, P = 0.742) for EMD (Figure 27).

However, statistically significant two-factor interaction between sex and time ($F_{(1, 98)}$ = 28.738, P < 0.01) for EMD were observed. The interactions showed a significantly longer EMD in females compared to males when fatigue is present. Additionally, significant main effects for time were demonstrated ($F_{(1, 98)}$ = 709.406, P < 0.01), indicating the EMD of hamstring muscles at 240°·s^{-1} was longer post-fatigue compared to pre-fatigue. For sex differences, the ANOVA analysis indicated that a statistically significant longer EMD post- fatigue at 240°·s^{-1} were observed in females compared to males.

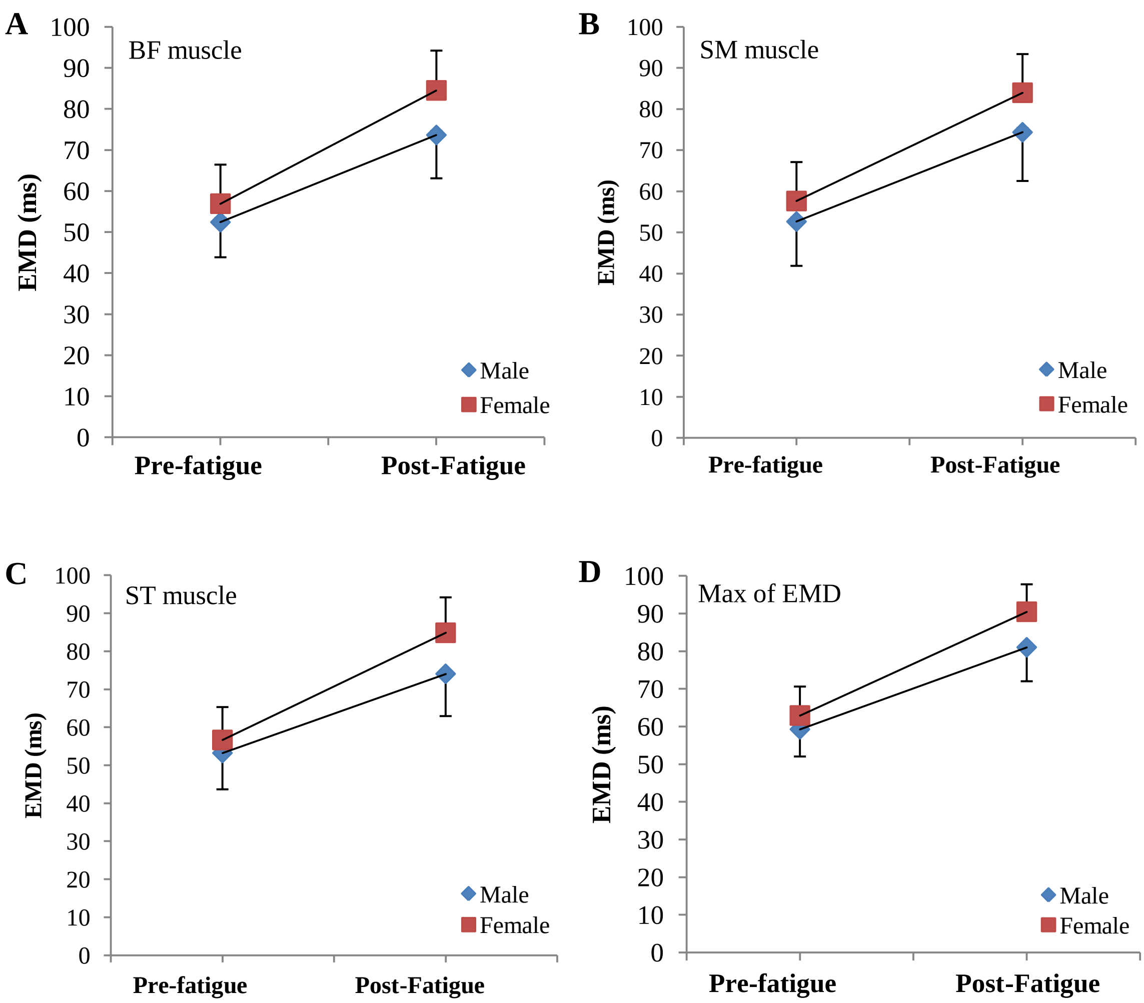


Figure 27 (A, B, C and D) EMD of hamstring muscles (BF, SM and ST and Max) at 240°·s^{-1} (mean ± SD) for males and females (pre-post fatigue).
Note: No significant interactions (sex × Hamstring muscle groups × time) for the EMD were observed. Statistically significant interactions (sex × time) for the EMD were observed. Significant main effects for the time were observed. Statistically significant longer EMD post- fatigue were observed in females compared to males.

6.3.6.4 Influence of fatigue on the EMD of males at all three angular velocities

A statistically significant two-factor interaction between angular velocities and time ($F_{(2, 98)}$ = 20.459, P < 0.01) for the EMD of hamstring muscles of males was observed (Figure 28). The interaction showed longer EMD in males as angular velocities increased when fatigue is present. Also a significant main effect for time was demonstrated ($F_{(1, 98)}$ = 709.406, P < 0.01), indicating the EMD of males was longer post-fatigue compared to pre-fatigue. Additionally, significant main effects for angular velocity was demonstrated ($F_{(2, 98)}$ = 1028.34, P < 0.01), indicating an increase in the EMD of males with increasing angular velocity (60, 120 and 240°·s^{-1}). There was was a greater effect of fatigue in the EMD of males at the fast angular velocity (240°·s^{-1}) compared with the slow (60°·s^{-1}). The fatigue effects were greater as the angular velocity increased.

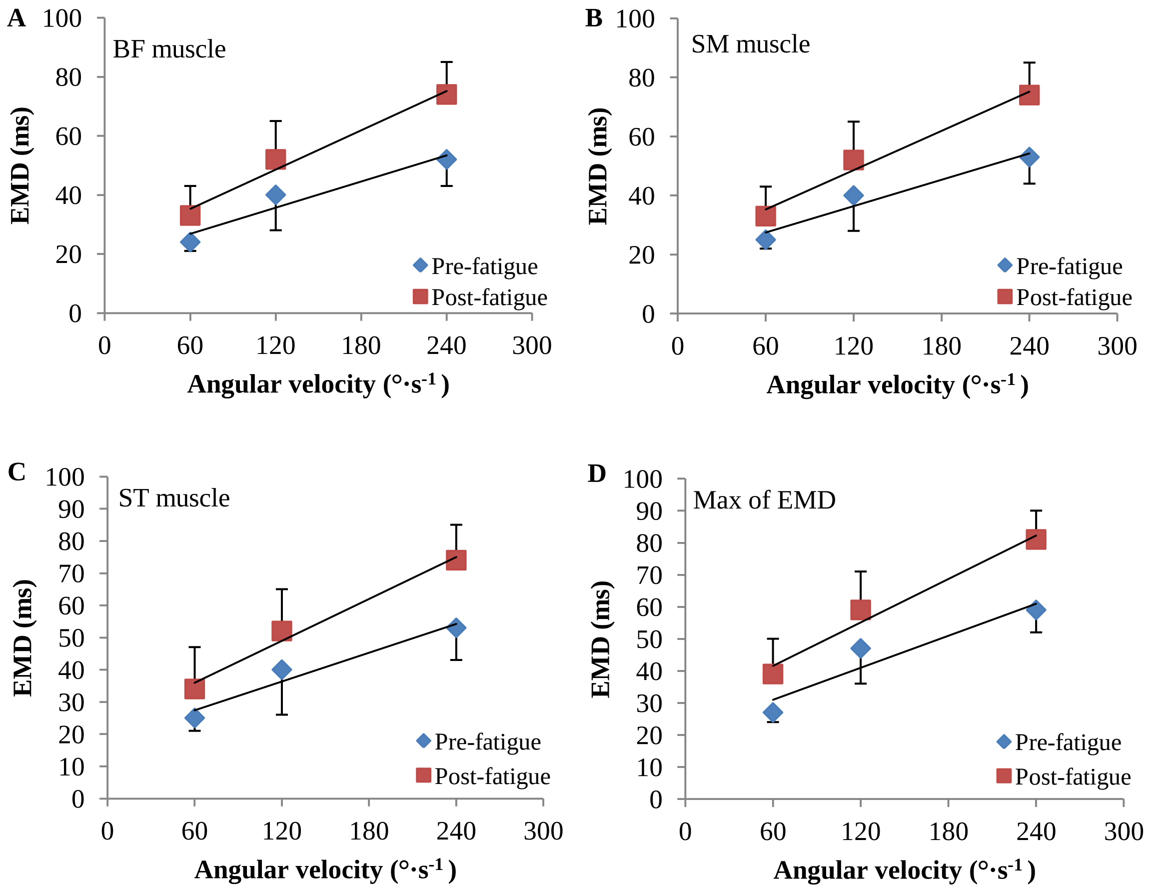


Figure 28 (A, B, C and D) EMD of hamstring muscles (BF, SM and ST and Max) at 60, 120 and 240°·s^{-1} (mean ± SD) for males (pre-post fatigue).

Note: A significant interactions (angular velocities × time) for the EMD were observed. Significant main effects for the time were demonstrated, indicating the EMD of males at all three angular velocities (60, 120 and 240°·s^{-1}) was longer in post-fatigue compared to pre-fatigue. Significant main effects for the angular velocity was demonstrated.

6.3.6.5 Influence of fatigue on the EMD of female at all three angular velocities

A statistically significant two-factor interaction between angular velocities and time ($F_{(2, 98)}$ = 20.459, $P < 0.01$) for the EMD of hamstring muscles of females was observed (Figure 29). The interaction showed longer EMD in females as angular velocities increased when fatigue is present. Also a significant main effect for time was demonstrated ($F_{(1, 98)}$ = 709.406, $P < 0.01$), indicating the EMD of females was longer post-fatigue compared to pre-fatigue. Additionally, significant main effects for angular velocity was demonstrated ($F_{(2, 98)}$ = 1028.34, $P < 0.01$), indicating an increase in the EMD of females with increasing angular velocity (60, 120 and 240°·s^{-1}). There was was a greater effect of fatigue in the EMD of females at the fast angular velocity (240°·s^{-1}) compared with the slow (60°·s^{-1}). The fatigue effects were greater as the angular velocity increased.

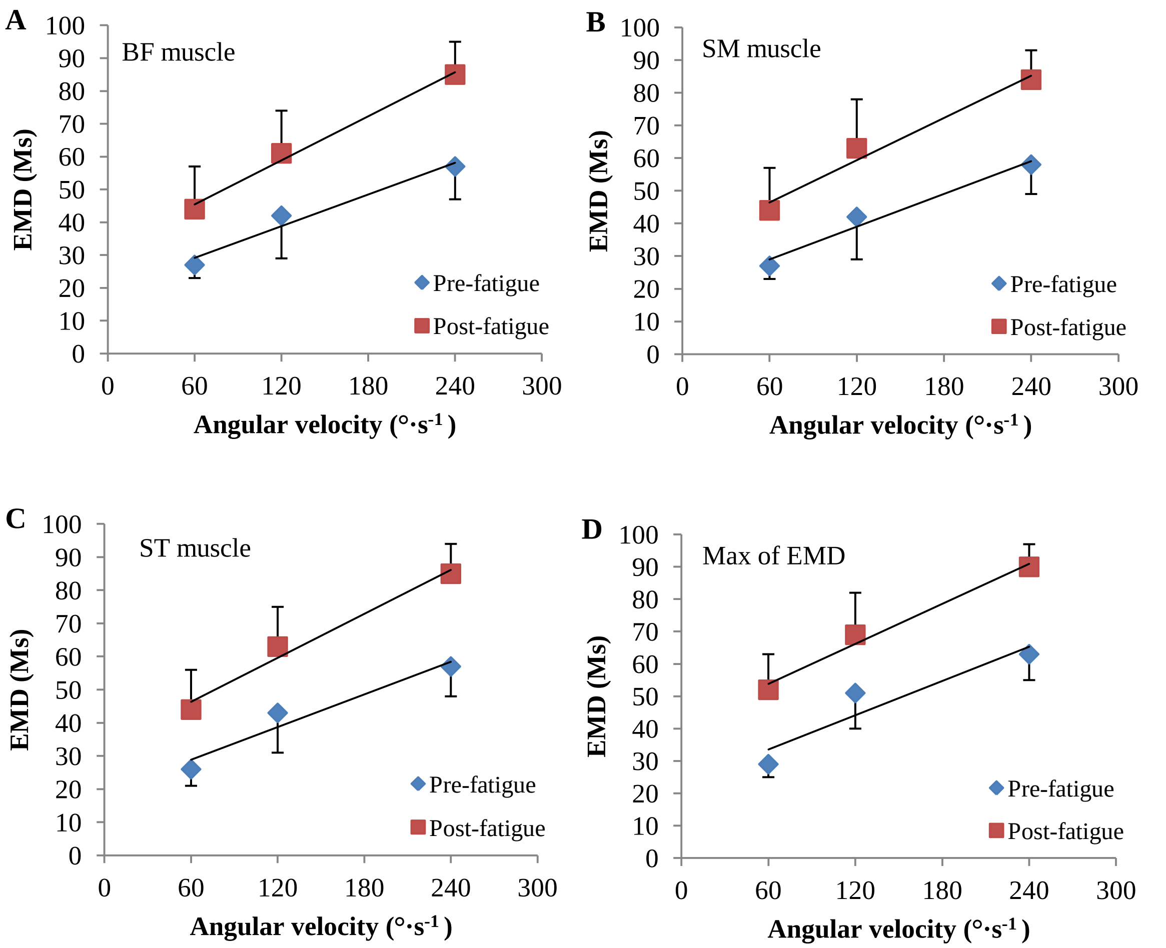


Figure 29 (A, B, C and D) EMD of hamstring muscles (BF, SM and ST and Max) at 60, 120 and 240°·s^{-1} (mean ± SD) for females (pre-post fatigue).
Note: A significant interactions (angular velocities × time) for the EMD were observed. Significant main effects for the time were demonstrated, indicating the EMD of females at all three angular velocities (60, 120 and 240°·s^{-1}) was longer in post-fatigue compared to pre-fatigue. Significant main effects for the angular velocity was demonstrated.

6.3.7 Summary of results

6.3.7.1 Influence of fatigue on sex differences in the FH/Q ratio

- A significant three-factor interaction between sex, joint angle and time for the FH/Q ratio were found. The interactions showed a significantly lower FH/Q ratio in females at three angular velocities (60, 120 and 240°·s^{-1}) compared to males when fatigue is present and higher when decreasing joint angle (closer to full knee extension).

- A statistically significant two-factor interaction between angular velocities and time for the FH/Q ratio of males was observed. The interaction showed an increase in the FH/Q ratio with increasing angular velocity especially when fatigue is present.
- Significant main effects for time, indicating that for all individuals (irrespective of sex, joint angle or angular velocity) the FH/Q ratio was lower post-fatigue compared to pre-fatigue.

6.3.7.2 Influence of fatigue on sex differences in the EMD

- No significant three-factor interactions between sex, hamstring muscle group and time for EMD were observed. However, statistically significant two-factor interactions between sex and time for EMD were observed. The interactions showed a significantly longer EMD in females at three angular velocities (60, 120 and 240°·s^{-1}) compared to males when fatigue is present.
- A statistically significant two-factor interaction between angular velocities and time for the EMD of hamstring muscles of males was observed. The interaction showed longer EMD in males as angular velocities increased when fatigue is present.
- Significant main effects for time, indicating that for all individuals (irrespective of sex or angular velocity) the EMD of hamstrings muscle was longer post-fatigue compared to pre-fatigue. Importantly the effect of fatigue was not similar in males and females as statistically significant interactions between sex and time for the EMD of hamstring muscles at all three angular velocities (60, 120 and 240°·s^{-1}) were found.

Chapter 7:

General Discussion

7.1. Overview of the main findings

The experimental studies included within this thesis (chapter 4-6) have generated original and significant findings on sex differences in the FH/Q ratio and neuromuscular performance prior to and following a downhill running fatigue task. The main findings demonstrated significant main effects for time, indicating that for all individuals (irrespective of sex, joint angle or angular velocity) the FH/Q ratio was lower and EMD of hamstrings muscle was longer post-fatigue compared to pre-fatigue. Importantly the effect of fatigue was not similar in males and females as statistically significant interactions between sex and time for the FH/Q ratio and EMD of hamstring muscles at all three angular velocities (60, 120 and 240°·s^{-1}) were found. The FH/Q ratio post-fatigue was lower in females compared to males, and EMD post-fatigue was longer in females compared to males. Additionally, irrespective of time, significant main effects for sex were demonstrated, indicating that the FH/Q ratio pre fatigue, as shown in study one (chapter 4), was lower in females compared to males and the differences increased post fatigue. However, as shown in study two (chapter 5), there were no sex differences in the EMD of the hamstrings muscle at all three angular velocities pre fatigue.

For angular velocity, significant main effects were found indicating that irrespective of sex or time, there was an increase in the FH/Q ratio with increasing angular velocity. Interestingly, the effect of angular velocity on FH/Q ratio was not similar in males and females, as statistically significant three-factor interactions for angular velocity, time and sex were found. The interactions showed a significantly higher FH/Q ratio in males compared to females especially when fatigue is present and with increasing angular velocity. There were also statistically significant interactions between angular velocity and time for the EMD of hamstring muscles with longer EMD as angular velocities increased post fatigue. However, irrespective of time, sex or angular velocity no significant main effects for the hamstring muscles were observed in the EMD. Additionally, irrespective of time or sex, significant main effects for the angular velocity were demonstrated, indicating a longer EMD of hamstring muscles with increasing angular velocity.

For joint angle, the main findings demonstrate significant main effects, indicating that irrespective of sex, or time there were increases in the FH/Q ratio with decreasing joint angle (closer to full knee extension). Importantly the effect of joint angle was not similar in males and females as statistically significant three-factor interactions between joint angle, time and sex for the FH/Q ratio were found. The interactions showed a significantly lower FH/Q ratio in females compared to males especially when fatigue is present and decreasing joint angle (closer to full knee extension). In study one (chapter 4), a significant two-factor interaction also was observed between knee joint angle, and sex for the FH/Q ratio pre fatigue. This interaction indicated that the FH/Q ratio increases closer to full knee extension and was higher in males compared to females especially with increasing angular velocity.

7.2. Influence of fatigue on the FH/Q ratio

One of the aims of the present investigation was to examine the effects of downhill running fatigue on the FH/Q ratio at different joint angles and angular velocities. Irrespective of sex, there was a significant main effects for time, joint angle and angular velocity, indicating that the FH/Q ratio at all three angular velocities was lower post-fatigue compared to pre-fatigue and the FH/Q ratio was higher at more extended positions. That which makes us accepts the hypothesis 9 which states that the effects of fatigue on FH/Q ratio will be significantly greater increases with decreasing joint angle (closer to full knee extension). In addition, percentage decline in the FH/Q ratio of males and females ranged between 4 to 24% which confirms the main effect of fatigue as Iga et al., (2006) has reported systematic bias in concentric and eccentric knee torque, although these improvements, 3 to 7 %, were relatively small. This effects is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles when fatigue is present. However, the recreated FH/Q ratio following a fatigue task is difficult to compare to the literature since no investigation has explored the effects of downhill running fatigue on the FH/Q ratio at action-specific angles. There was also an increase in the FH/Q ratio (irrespective of time) with increasing angular velocity. That which makes us accepts the hypothesis 10 which states that the effects of fatigue on FH/Q ratio will be significantly greater increases with decreasing angular velocity. These findings have important implications for dynamic knee stability when fatigue is present. Epidemiological data suggests that injury is more frequent in the fatigued stage after numerous repetitons of the same movement (Hawkins et al., 2001, Olsen et al., 2004). The data from the present study suggest that the FH/Q ratio is reduced when fatigue is present which might be a cause of the increased relative risk of injury.

The manifestations of functional changes occurring with fatigue are multiple and depend on the joint angle, angular velocity, action type (Green, 1997). Near full knee extension, static stability is reduced and functional stability relies mainly on dynamic stability to protect the knee structures (Griffin et al., 2006). In the current study, at decreased joint angles (closer to full knee extension) and in the fatigue state, the FH/Q ratio at all three angular velocities increases due to a larger decrease in the quadriceps concentric torque than in eccentric hamstrings torque. The stability systems are affected by changes in the joint angle, therefore observing the change in the angle-specific torque values following downhill running fatigue may be relevant to knee stability as it describes the joint angle at which specific muscle action is most effective. The current findings that the FH/Q ratio increases with decreased joint angle have been reported by several investigators (Coombs et al., 2002). However, the decreased FH/Q ratios following a fatigue task found in the current study are difficult to compare to the literature (Aagaard et al., 1998) since no investigation has investigated the effects of downhill running fatigue on the FH/Q ratio. This limitations should be taken into account when considering these findings regarding the nature of the fatigue protocol and interpretation of the results found. The issue with downhill running fatigue protocols also is that the high intensity muscle loading components specific to match play are not reproduced; cutting and braking manoeuvres and high intensity landings from jumps are not performed. Also, other studies have determined torque in a seated position with the hip flexed at 90° which is not functionally relevant, but despite this our findings are consistent with the extant literature. Aagaard et al., (1998) used females and male track athletes to investigate joint angle-specific FH/Q ratio and found that maximal eccentric strength was greater than maximal concentric strength for both the quadriceps and hamstring muscles. In addition, maximal quadriceps muscle strength was elevated when obtained at gradually more flexed joint angle positions (i.e., 50°,40°,30°). Conversely, maximal hamstring muscle strength was greater when obtained at gradually more extended positions (i.e., 30°,40°,50°). Furthermore, the FH/Q ratios for fast knee extension (4.19 rad.s^{-1}) were 1.0, 1.1, and 1.4 based on 50°, 40°, and 30° moments, respectively, and the corresponding values for slow knee extension (0.52 rad.s^{-1}) were 0.6, 0.8, and 1.0. Therefore, the FH/Q ratio was increased, as we found in the present study, with extended joint angle positions and with decreased joint angle at 0.52 rad.s^{-1} compared with 4.19 rad.s^{-1}. However, they ignored joint angles lower than 30°, where dynamic stability is often challenged. Coombs and Garbutt, (2002) used 9 females and 6 males recreational athletes to calculate joint angle-specific FH/Q ratio values throughout a 90° range of movement and found increasing FH/Q ratio values especially at 10°. Eccentric or concentric angle specific torque prior to and following fatigue may partly explain the increased FH/Q ratio. Therefore, to protect the knee joint, the FH/Q ratio should be higher at more extended knee positions especially when fatigue is present. Our findings demonstrated that, irrespective of sex, there was a significant main effect for joint angle, indicating that the FH/Q ratio at all three angular velocities was higher at more extended positions with lower post-fatigue compared to pre-fatigue. These data support and extend findings from previous literature indicating that functional stability is enhanced near full knee extension, even when fatigue is present.

Although direct comparisons are difficult, due to the differences in study designs and protocols, in agreement with many previous studies the exercise protocol that was designed to induce fatigue reduced the capacity of the knee extensor and flexor muscles to develop torque. Irrespective of joint angle or movement velocity, the reduction in strength was evidenced in the current study by a decline in eccentric and concentric peak torque. These observations agree with the results of Gleeson et al. (1995), who investigated the effect of a fatigue task (30 reciprocal maximal voluntary actions of the knee flexors and extensors) on isokinetic leg torque in eleven female collegiate soccer players using an isokinetic dynamometer at an angular velocity of 3.14 rad.s^{-1}. They reported that their fatigue protocol reduced the ability of knee flexors and extensors to generate torque during only concentric muscle actions at 3.14 rad.s^{-1} angular velocity. Kawakami et al. (1993) also found a decrease (45%) in PT of elbow muscles at three angular velocities (0.21, 0.52, and 1.05 rad.s $^{-1}$) during concentric and eccentric torque after 50 consecutive trials of maximal concentric and eccentric muscle actions. Following the same downhill running protocol as used in the present study, Eston et al., (1996) examined the effects of a prior bout of maximal isokinetic eccentric exercise on delayed onset muscle soreness in ten healthy male sports science students who were randomly allocated to either a treatment group (n = 5) or a control group (n = 5). Pre and post the fatigue trial, both concentric and eccentric isokinetic maximal knee extensors torque measurements were determined from a sitting position at angular velocities of 0.52 and 2.83 rad s^{-1}. The finding of their study reported an immediate post-fatigue loss in PT for both concentric and eccentric actions at the slow and fast angular velocities (0.52 and 2.83 rad.s^{-1}) The concentric PT values were reduced about 19% of the PT value at 0.58 rad s^{-1}, and decreased about 15% in the PT value at 2.83 rad s^{-1}. In the current study the findings also showed a decrease of about 19% of the concentric PT value at 1.05 rad s^{-1} and decrease about 9% of the concentric PT value at 2.09 rad s^{-1}, but there was an increase of about 9% of the concentric PT value at 4.19 rad s^{-1} which may be due to using different position, participants as well as angular velocity.

Despite the fact that Eston et al., (1996) only had 10 male participants, and that they measured torque in a seated position, we have found similar findings of a reduction in concentric and eccentric torque after an identical downhill running protocol. In comparison to the findings of the present study, the study of Eston et al., (1996) is limited by the fact that they: i) only investigated PT rather than exploring angle specific torques, and ii) only investigated knee extensors not eccentric flexors. In addition, the sample size of related previous studies is small and the assessments were also only at PT rather than angle-specific torques, and used a sitting position which not relevant to sporting activities. This is particularly important as we know that torque appears to be significantly greater for knee flexion in a sitting position when compared to the more ecologically valid supine position (Black et al., 1993). Therefore, direct comparison of torque obtained from seated versus supine or prone positions should be avoided. An advantage of the assessment of torque in the prone and supine position, as used in the present study, provide a closer approximation of the length tension relationship of the hamstring and quadriceps muscles during many functional and sporting activities, and is therefore functionally relevant (Worrell et al., 1990).

The ‘conventional’ ratio is the most widely reported ratio in the literature and is calculated by dividing the concentric hamstrings PT by the concentric quadriceps PT (H/Q ratio). After bout of eccentric exercise (4 sets of 10 repetitions for the leg press, leg extension, and leg curl exercises at 120% of the concentric one repetition maximum) Thompson et al., (2011) found a significant decrease at 1.05 rad s^{-1} in isokinetic leg flexion and extension PT at 24, 48, and 72 h post exercise. The percent change values were not different for both isokinetic leg flexion and extension at 24, 48, and 72 h post exercise and also the eccentric exercise protocol did not influence the conventional H/Q ratio. These findings are similar to those reported by Byrne and Eston, (2002) who demonstrated that an intense eccentric bout of exercise reduced concentric isokinetic strength by 12–22 % for the leg extensors at 24–72 h post-exercise. However, the studies looking at the FH/Q ratio which compares eccentric muscle actions to concentric muscle actions of the opposing muscles are more relevant to the present study (Aagaard et al., 1995, Hole et al., 2000). The findings of the present study demonstrated that the FH/Q ratio was decreased significantly post fatigue. This is attributed to relatively lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles when fatigue is present. The current findings are in agreement with previous investigations related to the FH/Q ratio in the fatigued state (Rahnama et al., 2003, Small et al., 2010) however, there are also some conflicting findings in the literature. Wright et al., (2009) assessed the effect of fatigue on two muscle strength ratios, the conventional ratio and the FH/Q ratio, and the co-activation of hamstrings and quadriceps during isokinetic knee flexion/extension. They found a significant increase in both the conventional ratio (0.75 vs. 1.02) and the FH/Q ratio (0.88 vs. 1.08) following a fatiguing protocol consisting of 50 maximal concentric knee flexion/extension repetitions. It was also found that the co-activation of the hamstrings during concentric quadriceps muscle actions significantly increased; however, during concentric hamstring muscle actions the co-activation of the quadriceps did not significantly change. It has been proposed that during knee extension antagonistic eccentric, not concentric, hamstrings co-activation decreases the anterior shear forces induced by the concentric quadriceps muscle group action (Senter and Hame, 2006). The results of the 40 min intermittent downhill run protocol in the present study indicate that both muscle groups fatigued in accordance to previous literature (> 50% drop off from PT output). It can therefore be concluded with confidence that the protocol used in the present study was sufficient in fatiguing both muscle groups, but a greater reduction was found in eccentric hamstrings torque compared to concentric quadriceps torque inducing a decreased FH/Q ratio post-fatigue which was in agreement with Rahnama et al., (2003) and Small et al., (2010). On the other hand, other investigations have shown a greater decrease in peak concentric quadriceps torque following concentric fatigue tasks (Garrandes et al., 2007, Grabiner and Owings, 1999) and a limited reduction in peak hamstrings eccentric torque following fatiguing eccentric actions (Warren et al., 2000). The contradictory findings may be attributed to the nature of the fatiguing protocol (including the mode and intensity of exercise, the nature of loading during muscle activation and the environment) and proportion of concentric vs. eccentric work performed, which would influence the mechanisms of fatigue (Maluf and Enoka, 2005). The physiological changes which result from eccentric exercise that reduce the aforementioned effects are as yet unknown.

The diferences in the direction of the fatigue induced change in FH/Q ratio may be explained by the nature of the protocols used, and protocols based on CON/ECC or ECC/ECC reciprocal actions should be developed and validated against sport-specific protocols when testing is constrained to the use of an isokinetic dynamometer. Since the eccentric action relies mainly on mechanical factors generating force, repeated actions result in an increased compliance of muscle fibre that may explain the small decrease in torque observed in study of Wright et al. (2009). Interestingly though, studies that also found a reduction in the FH/Q ratio post fatigue have differences within their protocols. Rahnama et al. (2003) and Small et al. (2010) used a football-specific intermittent treadmill protocol with professional players to replicate fatigue during match play, while in the current study fatigue was defined as a torque decline after 40 min of intermittent bouts (i.e., 5 × 8 min) at a -10% decline on a motorised treadmill. Although these fatiguing protocols would increase the demand of the hamstrings to work eccentrically, the samples size in Rahnama et al., (2003) and Small et al., (2010) studies were small and the duration of the fatiguing protocols were long (90 min). Therefore, the study of fatigue using downhill running, as used in the present study, will increase eccentric loading more than fatigue protocols used in previous studies, and will more appropriately highlight the typical mechanisms of hamstring and knee injury.

Although limited, research has been carried out on the effect of fatigue on FH/Q ratios. Following a downhill running fatigue protocol, the findings of the present study show a greater decrease in eccentric hamstrings compared to a decrease in concentric quadriceps torque. These data contribute to the literature aiding the future development of the FH/Q ratio and its use in injury prevention and rehabilitation strategies. Delextrat et al., (2010) investigated the effects of fatigue induced by a field test representative of soccer specific movements on both conventional H/Q (calculated as the maximal concentric hamstrings strength divided by the maximal concentric quadriceps strength) and FH/Q ratios (calculated as the maximal eccentric hamstrings strength divided by the maximal concentric quadriceps strength) in the dominant and non-dominant legs at two different velocities (l.05 rad s^{-1} and 3.14 rad s^{-1}). They found significant decreases in the conventional H/Q ratio in the dominant leg at 3.14 rad s^{-1} and in the FH/Q in the dominant leg at l.05 rad s^{-1} and 3.14 rad s^{-1}. Oliveira et al., (2009) have verified the effects of heavy-intensity continuous running exercise on theconventional H/Q and FH/Q ratios, where no differences were found for the conventional torque ratios, however, the functional torque ratios at 180°/s decreased significantly after running. The deficit in eccentric hamstrings torque with fatigue is of concern in that it may correspond with a compromised capability for joint stabilisation and, potentially, an increased risk of injury (Rahnama et al., 2003). Small et al. (2010) recently investigated the effect of multidirectional soccer-specific fatigue on hamstring muscle strength. They found that eccentric hamstring PT decreased significantly during each period of exercise and the functional hamstring/quadriceps ratio also decreased significantly during each period which may have implications for the increased predisposition to hamstring strain and knee joint injury. With the exception of only one prior study, our findings are in agreement with all other previous studies. According to our knowledge, all previous studies measured only PT to determine the FH/Q ratio, which is not functionally relevant as eccentric and concentric PT does not occur at the same joint angle. Therefore, the present study is the first study to show a decrease in FH/Q ratio at PT and at functionally relevant angles.

The ability of knee stabilising systems are affected by changes in the joint angle, therefore observing the change in FH/Q ratio at specific angles following downhill running fatigue may be more relevant. The present findings that the FH/Q ratio increases post fatigue when calculated at three angular velocities, and that increases are greater closer to full knee extension have been reported by several investigators (Aagaard et al., 1998, Coombs and Garbutt, 2002). The fatigue effects are therefore more important at extended joint positions. However, no study has previously shown a significant main effect for joint angle and the greater increase in the ratio at PT or mid range movement. However, if looked at positions closer to full knee extension, according to the finding of current study, fatigue effects are less.

In downhill running, the extensor muscles of the lower limbs eccentrically contract during each stride to decelerate the center of mass after the foot touches the ground (Walmsley et al., 1978). Eccentric muscle action through downhill running has been associated with increased mechanical stress (Iversen and McMahon, 1992). In the present study a significant main effect for time was observed, indicating that the FH/Q ratio at all three angular velocities was lower post-fatigue compared to pre-fatigue and the FH/Q ratio was greater at more extended positions. Differences in protocols have a marked influence on the change in FH/Q ratio following fatigue mainly due to the differences in eccentric hamstrings and concentric quadriceps loading. The reduction in muscle torque due to fatigue is likely to be due to a decrease in the number of fibres that can be recruited to generate force as fibres already recruited begin to fail (Bangsbo, 1994). The decrease in hamstring co-activation following fatigue in the present study may decrease the stability of the joint and not act as a natural safety mechanism during knee extension. Eccentric muscle actions possess several unique features which may explain why they are associated with muscle damage. They are characterized by lengthening of the muscle whilst the muscle attempts to contract. During shortening actions, work is done by the muscle, but during eccentric action, work is done on the muscle by the external lengthening forces (Eston et al., 2003). Eccentric forms of exercise are interesting, because usually greater strength and tension values are attained than in concentric or isometric form. It is unclear whether this is accompanied by elevated metabolic stress to the exercised musculature. Horstmann et al., (2001) suggest that usually eccentric exercise leads to less acute fatigue and lower lactate and ammonia reaction than concentric exercise in comparable work levels. However, the protocol used in the present study may have elicited a higher eccentric compared to concentric load. Evidence of lower neuromuscular activity in spite of greater strength development in the eccentric action than in concentric action forms of exercise (Verdonck et al., 1994) which supports the emphasis on mechanical stress. It remains uncertain whether the lower metabolic stress might be useful during the training process. A greater scope of training and increased number of training stimuli might be applied in primarily eccentric forms of exercise. The mechanism of force generation during an eccentric action also differs, whereby the cross-bridges are detached mechanically and with greater force rather than undergoing a detachment that involves adenosine triphosphate (ATP) splitting, as with concentric actions. The compliant portion of individual cross-bridges is also stretched further during an eccentric versus an isometric action (Enoka, 1996). In addition, eccentric actions performed at long muscle length result in greater damage than those performed at short muscle length (Newham et al., 1988).

The observations of the present study further support suggestions that FH/Q ratio is more suitable to recognise the ability of the knee flexors in stabilising the joint than the conventional ratio. This is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles. This is due to the lower maximal capacity of the hamstrings compared to the quadriceps. In addition, fatigue is not a single event that leads to a decline torque but a multitude of effects that act together causing this decline potential relative risk of injury (Enoka and Stuart, 1992). The findings of the present study showed a significant decrease in the FH/Q ratio when fatigue is present. This decline is due to the relatively greater reduction in eccentric vs. concentric torque production. These findings are in agreement with previous studies that have used varying fatigue protocols. However, this is the first study to have explored these effects in a functionally relevant position (e.g. prone) and exploring angle specific torque as well as a range of movement velocities.

7.3 Influence of sex differences on the response to fatigue for the FH/Q ratio

The current study appears to be the first to have examined the influence of sex differences on the response to fatigue associated changes in the FH/Q ratio at different joint angles and angular velocities. Irrespective of time, joint angle or angular velocity, significant main effects for sex were demonstrated, indicating that the FH/Q ratio was lower in females compared to males and the differences between males and females in FH/Q ratio was significantly smaller in pre fatigue compared to post fatigue. Percentage decline in the FH/Q ratio of males ranged between 6 to 15% and 4 to 24% for females which confirms that the effect of fatigue on males and females is different as the FH/Q ratio was lower in females compared to males. This difference may be due to the bigger efforts of the hamstrings of females than males in the control of running activities and for stabilizing the joint angle during foot contact with the ground (Rahnama et al., 2003). This greater decline with fatigue in females may lead to lower stability of the knee and thus lead to a greater relative risk of injury. Additionally, the main findings demonstrate statistically significant three-factor interactions between sex, joint angle and time for the FH/Q ratio for all three angular velocities. The interactions showed that irrespective of time, a significantly lower FH/Q ratio in females compared to males was observed, especially when fatigue is present and with decreasing joint angle (closer to full knee extension). The main findings also demonstrate statistically significant three-factor interactions between sex, angular velocity and time for the FH/Q ratio. The interactions showed that irrespective of time, a significantly lower FH/Q ratio was observed in females compared to males and there were increases in the FH/Q ratio with increasing angular velocity. Importantly the effect of fatigue was not similar in males and females as statistically significant interactions between sex and time for the FH/Q ratio at all three angular velocities were found. The interactions showed a significantly lower FH/Q ratio post fatigue in females compared to males. In the fatigue state the FH/Q ratio of males and females increases with angular velocity due to a larger decrease in the quadriceps concentric torque than in eccentric hamstrings torque. The stability systems of males and females are affected by changes in the joint angle and angular velocity. The change in the angle-specific torque values following downhill running fatigue may be relevant to knee stability. As velocity of motion increases, the forward momentum of the tibia increases to a point where increased hamstrings recruitment is required to limit both extension rotation and anterior translation of the joint (Hewett et al., 2008). Therefore, the findings of the present study confirm that as angular velocity increases males and females increase their hamstrings to quadriceps PT output in order to stabilise the joint and protect the ACL. That which makes us accepts the hypothesis 7 which states that the FH/Q ratio will significantly decrease post-fatigue compared to pre-fatigue task with greater decrease in FH/Q ratio in females compared to males

Irrespective of time or angular velocity, the present study findings demonstrated significant main effects for joint angle, indicating that the FH/Q ratio was significantly higher in males compared to females and the differences between males and females were greater at more flexed knee positions. The current findings that the FH/Q ratio increases with decreased joint angle have been reported by several investigators (Aagaard et al., 1998, Coombs et al., 2002). However, the increased FH/Q ratios following a fatigue task found in the present study are difficult to compare to the literature since the effects of downhill running fatigue on sex differences in the angle-specific torque values have not been previously investigated. Aagaard et al. (1998) used female and male track athletes to investigate joint angle-specific FH/Q ratio and found an increase in the FH/Q ratio with decreased joint angle at 0.52 rad s^{-1} and 4.19 rad s^{-1}. However, they ignored joint angles lower than 30°, where dynamic stability is often challenged. Also other studies have determined torque in a seated position with the hip flexed at 90° which is not functionally relevant, but despite this our findings are consistent with the extant literature. Coombs and Garbutt, (2002) used 9 females and 6 males recreational athletes to calculate joint angle-specific FH/R ratio values throughout a 90° range of movement and found increasing FH/R ratio values especially at 10°. To protect the knee joint, the FH/Q ratio should be higher at more extended knee positions especially in females and when fatigue is present. Our findings show that irrespective of sex, there was a significant main effect for joint angle, indicating that the FH/Q ratio at all three angular velocities was higher at more extended positions with lower values post-fatigue. These data support current literature indicating that functional stability is enhanced near full knee extension, even when fatigue is present.

Females, with decreased PT of the hamstrings relative to the quadriceps may be at increased risk of ACL injury, particularly at high joint velocity (Hewett et al., 2008, Knapik et al., 1991). The present findings demonstrated that irrespective of time, sex or joint angle, significant main effects for angular velocity were found, indicating that the FH/Q ratio was significantly lower in females compared to males and the FH/Q ratios were increased with increasing angular velocity. The current findings that the FH/Q ratio increases with increasing angular velocity have been reported by several investigators (Hewett et al., 2008, Hewett et al., 2005). However, the FH/Q ratios in males and females following a fatigue task at specific angular velocities found in the current study are difficult to compare due to a lack of previous studies. Hewett et al., (2008) also demonstrated that with increased knee angular velocities, approaching those that occur during sports activities, significantly greater FH/Q ratios were observed in male than female athletes. The observed sex difference in the relationship between increasing FH/Q ratio and velocity would be consistent with females' decreased ability to dynamically control the joint angle during sports activities (Hewett et al., 2004, Hewett et al., 2005). Aagaard et al., (1995) asserted that eccentric hamstrings torque during deceleration minimises anterior shear forces at the proximal tibia and improves dynamic functionality of the joint. The hamstrings muscles work synergistically with the ACL to resist quadriceps contraction during knee extension. The relative activity of the hamstrings is increased as the ligament is loaded by quadriceps contraction at knee flexion angles below 45° via the spinal level reflex arc between the ACL and the hamstrings (Solomonow et al., 1987). The absence of increased hamstrings muscle torque relative to quadriceps muscle torque may decrease the ability to control coronal and sagittal plane knee motion in female athletes, and may increase strain on the knee and may predispose females to a higher rate of injury than males (Hewett et al., 2005, Markolf et al., 1995).

The increased sex differences in FH/Q ratio following a downhill running fatigue task is difficult to compare with the literature since no investigation has specifically investigated that. Pincivero et al., (2003) reported that men exhibited higher knee flexion and extension torques as well as greater work and power production when compared to women, however it was reported that the men fatigued quicker during maximal effort muscle concentric actions and during sub-maximal contractions men and women fatigue at the same rates but men still exhibited greater torque productions during knee extension. Specifically, males were observed to produce significantly greater knee extensor and flexor peak torque, work, and power than females when corrected for body mass; as a result, the males exhibited a greater rate of muscle fatigue than the females (Pincivero et al., 2003). This suggests that greater initial torque production might be a reason for greater degree of fatigue. The findings of the present study also show a greater decrease in eccentric hamstrings torque compared to a decrease in concentric quadriceps torque in females and males when fatigue is present and the significant sex differences were increased when fatigue was present. This is due to females maintaining eccentric torque when fatigue is present more than the males irrespective of joint angle or movement velocity.

It is well recognized 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). A recent study of Small et al. (2010) has indicated that the FH/Q ratio significantly decreases at the end of each half of a soccer match using a simulated soccer specific fatiguing task. There appear to be no comparable data available but if fatigue has a similar effect on males and females then the ability to resist fatigue and maintain joint stability should form a major part of prevention programmes. Work by Kawakami et al., (1993) suggested that at least for the elbow flexors, concentric and eccentric torque production decreases at a similar rate with advancing muscular fatigue . These limited data would suggest that the FH/Q ratio would remain similar in the fatigued and non-fatigued state in males and females. However, although limited, research has been carried out on the effect of fatigue on FH/Q ratios in males and females. Following the downhill running fatigue protocol, the findings of the present study show a greater decrease in eccentric hamstrings torque compared to a decrease in concentric quadriceps torque in females and males with greater decrease in females compared with males. These data contribute to the literature aiding the future development of the FH/Q ratio and its use in injury prevention and rehabilitation strategies.

In the current study, greater decline in FH/Q ratio was observed with fatigue in females compared with males. It is not easy to ascribe physiological reasons for the differences in fatigue between the quadriceps and hamstrings in females and males, but this highlights the degree to which muscular fatigue is probably specific to both muscle group and muscle action (De Ste Croix et al., 2009a). Therefore, it is possible that females had more hamstrings fatigue than males. To date, evidence demonstrates that males possess an inherent ability to generate (irrespective of muscle action) higher absolute levels of torque than females, and that females appear to experience muscle fatigue at a slower rate. Another aspect of the supply side of this function is metabolic substrate utilisation. A few studies have suggested that muscles of men may contain a slightly greater amount of fast, type II myosin, as indicated by differences in the type II: type I fibre area ratio

(Jaworowski et al., 2002, Holmback et al., 2003). As the type II fibres have greater ATPase rates (Sieck et al., 1998), this might be expected to elevate the rate of ATP consumption in men versus women, to some degree. Numerous studies show that ATP is well maintained during even high-intensity muscular activity (Kent-Braun et al., 2002, Lanza et al., 2005), so the pathways of ATP re-synthesis are sufficient to compensate for any potential differences in metabolic demand between sexes.

Reduced eccentric hamstrings torque strength relative to concentric quadriceps torque is implicated as a potential mechanism for increased lower extremity injuries (Myer et al., 2004, Knapik et al., 1991) especially in females and when fatigue is present. Imbalances in hamstrings to quadriceps torque (i.e., hamstrings to quadriceps PT ratios, H/Q < 0.75) and bilateral hamstrings strength correlate to greater incidence of lower extremity injury in female collegiate athletes (Knapik et al., 1991). The findings of present study demonstrated that females FH/Q ratio is reduced with fatigue more than males, and is lower initially prior to fatigue. Therefore, this finding would suggest that the FH/Q ratio is a mitigating factor for ACL tears especially when fatigue is present because the FH/Q ratio is reduced in females with fatigue more than males which might be cause for increased relative risk of injury.

7.4 Influence of fatigue on the EMD

One of the aims of the current investigation (chapter 6) was to examine the effects of downhill running and associated fatigue on the EMD of the hamstring muscles during eccentric muscle actions. For all individuals (irrespective of sex or angular velocity), there was a significant main effect for time indicating that the EMD for all hamstring muscles was longer post-fatigue compared to pre-fatigue. That which makes us accepts the hypothesis 8 which states that the EMD will significantly increase post-fatigue compared to pre-fatigue task with a greater increase in EMD in females compared to males. In addition, percentage decline in the EMD of males and females ranged between 8 to 28% which confirms the main effect of fatigue as a recent study of Lacourpaille et al., (2012) has suggested that inter-day reliability of EMD, was good (coefficient of variation ranged from 6.8% to 12.5%, i.e. SEM lower than 0.79 ms). This observation could be attributable to a number of mechanisms such as metabolic inhibition of the contractile process; excitation-contraction coupling failure as well as structural changes that have been suggested to explain peripheral fatigue (Pasquet et al., 2000, Gibala et al., 1995, Baker et al., 1993). In addition, for all individuals (irrespective of sex or time) findings of the present study demonstrated a statistically significant main effect for angular velocity, indicating a longer EMD for all hamstring muscles with increasing angular velocity. That which makes us accepts the hypothesis 12 which states that irrespective of sex or time, the EMD will be significantly longer as velocity movement increase. There were also statistically significant interactions between angular velocity and time for the EMD for all hamstring muscles with longer EMD as angular velocity increased post fatigue. These results suggest that neuromuscular hamstring function is impaired following downhill running fatigue and may limit dynamic knee joint stability, potentially contributing to the greater ACL injury risk.

The EMD has been found to be influenced by the type of muscle contraction (Cavanagh and Komi, 1979), joint angle (Grabiner, 1986), the level of effort (Grabiner, 1986; Vos et al., 1991), fatigue (Nilsson et al., 1977, Kroll, 1974) and the age and sex of the participants (Clarkson and Kroll, 1978, Bell and Jacobs, 1986). However, most studies of neuromuscular activity and fatigue have evaluated isometric muscle actions in male participants. Isometric actions may not be representative of muscle activity and fatigue development during human locomotion (Green, 1995). Therefore, it is difficult to compare the data from the present study to the extant literature as this is the first study to have examined the effects on fatigue on sex differences of the hamstring muscles during functionally relevant eccentric muscle actions. In the present study, the changes with fatigue were accompanied by a marked lengthening in EMD in all of the hamstring muscles (24 vs 44 ms at 60°·s^{-1}, 40 vs 62 ms at 120°·s^{-1} and 52 vs 90 ms at 240°·s^{-1}). Irrespective of time, this finding is in line with previous studies that have described increased EMD with increasing movement velocity but those studies determined EMD during concentric muscle actions before and after fatiguing dynamic exercise (Horita and Ishiko, 1987, Nilsson et al., 1977). Nilsson et al. (1977) have also reported an increase in EMD of the vastus lateralis muscle (VL) during concentric muscle actions from 95 ms at rest to 121 ms after 100 maximal isokinetic knee extensions, in which the peak torque, work and power all decreased by approximately 50%. Horita and Ishiko (1987) have reported that the median frequency of the surface EMG recorded from vastus lateralis during concentric muscle actions was decreased while the time lag of torque production after the onset of EMG was increased during exercise. These changes (median frequency and EMD) corresponded well to muscle lactate accumulation in the same muscle. However, Vos et al. (1991) reported in only seven males participants no significant change in EMD of the quadriceps femoris muscle following 150 sub-maximal (50% MVC) isometric knee extensions. Zhou et al., (1996) have also found that EMD of knee extensors were similarly elongated after only 25 maximal isometric knee extensions in six previously untrained healthy men. The conflicting finding with Vos et al. (1991) study may be attributed to the influence of the type of muscle contraction (Cavanagh and Komi, 1979), joint angle (Grabiner, 1986), the level of effort (Grabiner, 1986; Vos et al., 1991), fatigue (Nilsson et al., 1977, Kroll, 1974) and the age and sex of the participants (Clarkson and Kroll, 1978, Bell and Jacobs, 1986). A shorter EMD would be expected in a muscle which has a higher percentage of fast twitch (FT) fibres, greater contraction force and rate of force development (RFD). A shorter EMD would therefore be expected in the motor responses that recruit mainly FT motor units. The EMD, which is a component of the reflex time, is important for sports performance as it affects muscle response to sudden movements. Zhou et al., (1996) have also found that EMD of knee extensors were elongated after only 25 maximal isometric knee extensions in six previously untrained healthy men. Thus, EMD lengthening accompanies muscle fatigue induced by either isometric or dynamic exercise with maximal effort. However, no previous studies have directly examined the effects of fatigue on the EMD in hamstring muscles during eccentric actions, which is more functionally relevant to co-contraction of the knee during extension movements.

Clinically, alterations in the EMD of the hamstring muscle-tendon unit could compromise knee integrity and/or impair performance by modifying the transfer time of muscle tension to the tibia. Previous studies highlighted the importance of changes in EMD during physical activities. Vos et al., (1991) observed that changes in EMD might play an important role in the organization of the movement and probably result in impairment of neuromuscular control, through its relationship with the reflex time. To our knowledge, only two published studies have explored the effects of eccentric fatigue on EMD, following sub-maximal stretch-shortening exercise in males. The results of Strojnik and Komi, (1998) observed no impairment to electrically evoked EMD after maximal stretch-shortening cycle exercise, despite considerable decrements to volitional peak force and rate of force development capability, whereas Howatson, (2010) reported that a bout of maximal lengthening actions was responsible for a significant increase in EMD during both isometric and concentric actions (for isometric the EMD values were 62ms pre exercise, 81ms 48 h post exercise,82ms 96 h post exercise and for concentric the EMD values were pre exercise 63ms, 48 h post exercise 79ms and 96 h post exercise 90ms). However, the main findings of the present study confirmed that muscular fatigue elongated EMD during eccentric actions with an influence of angular velocity. The conflicting findings of Strojnik and Komi (1998) compared with the results of the present study may be due to the different muscle groups examined, the muscle actions, or that they explored electrically evoked EMD and/or different methods for calculating EMD. However, the present findings, together with corroborating findings from other studies (e.g., Gleeson et al. 1998b; Zhou et al. 1996), may suggest a reduced capability of the dynamic stabilisers to provide forceful corrective responses to mechanical loading of the knee from a neuromuscular perspective when fatigue is present. Such fatigue-related changes in neuromuscular performance may be interpreted to represent an increased risk of injury (Chan et al., 2001, Gleeson et al., 1998b, Mercer et al., 1998), which may be amplified particularly at knee angles where key ligamentous structures are already under greatest mechanical strain (e.g., near full knee extension) (Beynnon and Johnson, 1996).

The main proposed mechanism for the lengthening of EMD with fatigue is from the excitation-contraction coupling contractile mechanisms and the stretching of the series elastic components (SEC), resulting in prolonged EMD (Shi, 1996). After stimulation, the rate of calcium ions (Ca^{2+}) release from the sarcoplasmic reticulum (SR) has been shown to require 2-3 ms to reach its peak level (Zhou et al., 1996), which would account for approximately 5%-7.5% of an EMD time of 40ms. Impaired membrane conductivity with fatigue could reduce the sarcoplasmic reticulum (SR) Ca^{2+} release and therefore, contribute to the reduced rate of force generation and prolonged EMD during fatigue (Westerblad et al., 1991). Thus, it has been suggested that intense muscle actions may reduce SR Ca^{2+} release (consequently increasing the time to reach its peak), Ca^{2+} sensitivity and force production, and prolong EMD (Westerblad et al., 1991, Horita and Ishiko, 1987, Maclaren et al., 1989). It would appear therefore that the prolongation of the EMD during fatigue may be largely attributed to the failure of the muscle contractile process. If the major influencing factor of EMD is the time for the contractile components to stretch the series elastic component (SEC), increases in the percentage of type II fibres, contractile force and rate of force development may alter the EMD time. As has been demonstrated in the previous studies, there are significant correlations between EMD and isometric contractile properties (Viitasalo and Komi, 1981; Zhou et al., 1995). Furthermore, Cavanagh and Komi, (1979) have suggested that the duration of EMD is affected by the time necessary to stretch SEC of the muscle to a point where muscle force can be detected. The current study clearly demonstrated an elongation of EMD with fatigue. In response to this findings, a large mechanical component due to eccentric actions, therefore it is suggested that, eccentric training should be conducted to improve the neuromuscular performance and to hopefully reduce the relative risk of injury.

The initial muscle length affects the EMD monitored at 90° of knee extension may not be comparable to other knee joint positions. The experimental variations in EMD performance are likely to reflect the influence of joint angle on the degree of myofilament overlap (McComas, 1996), the discharge properties of the motoneurons and the capability for neural activation (Komi et al., 2000) and also the compliance characteristics of the musculo-tendinous complex (Muraoka et al., 2004). Whereas it is not possible to quantify the relative effects of each of these processes in the current study, under most circumstances the majority of the EMD is determined by the time required to stretch the series elastic component (SEC) (Granata et al., 2000, Kubo et al., 2000, Muraoka et al., 2004, Zhou et al., 1998). In a recent study, Minshull et al., (2011) have shown that volitional and magnetically-evoked peak force and EMD of the quadriceps femoris at joint angles proximal to full knee extension were enhanced by increased knee flexion. These findings suggested that EMD is worse at extended knee positions where injury is more likely to occur. However, bigger relative improvements in volitional compared to evoked indices of neuromuscular performance were observed with increasing flexion from 25° to 45°. These findings suggest that the extent of the relative differential between volitional and evoked neuromuscular performance capabilities is joint angle-specific and not correlated with performance capabilities at adjacent angles, but tends to be smaller with increased flexion. The existing literature has examined EMD at a range of joint angles making comparisons difficult. Those greater angles of knee flexion elicited superior (i.e. shorter) EMD is consistent with previous findings (e.g. Chan et al., 2001). The observed variations in EMD performance are likely to reflect the influence of joint angle on the degree of myofilament overlap (McComas, 1996), the discharge properties of the motoneurons and the capability for neural activation (Komi et al., 2000) and the compliance characteristics of the musculo-tendinous complex (Muraoka et al., 2004). While it is not possible to quantify the relative effects of each of these processes in the current study, under most circumstances the majority of the EMD is currently understood to be determined by the time required to stretch the series elastic component (SEC) (Zhou et al., 1998; Granata et al., 2000; Kubo et al., 2000; Muraoka et al., 2004).

Also, the fatigue pattern may not be replicated in other knee joint positions as Arendt-Nielsen et al., (1992) and Weir et al., (1996) have both shown. All of the available adult studies seem to show a significant increase in EMD after fatiguing trials, irrespective of muscle group, or muscle action examined, which would predispose the knee to greater injury risk. The current study clearly demonstrated an elongation of EMD after downhill running fatigue which may be attributed to the failure of the muscle contractile process. It is likely that this reflected impaired contractile mechanisms, increased compliance of the series elastic components (SEC), with a reduction in muscle fibre conduction velocity. But how the elastic properties of the muscle affect EMD during fatigue is not clear. The mechanisms involved in the increase in EMD after fatigue could be due to the deterioration in muscle conductive, contractile or elastic properties and requires further study. Irrespective of sex or angular velocity, the finding of current study is the first to demonstrate the influence of fatigue on the EMD of the hamstrings during eccentric actions, and therefore muscular fatigue should be considered an important factor in impaired neuromuscular mechanisms for eccentric functioning. This limitations should be taken into account when considering these findings regarding the condition of the participants may also not be guaranteed as there is no control to the daily life of them, they may not in the best condition when having the test, which affect the validity of the results

The passive component refers to the tendon which is responsible for the major portion of the series elasticity. The active component resides in the contractile proteins which bear tension when the muscle contracts. Since both muscle force and the active component of SEC depend upon the number of crossbridges attached, it has been reported that the stiffness of the active part of SEC increases with increases of muscle tension (Shorten, 1987). Aura and Komi, (1987) have suggested that the crossbridges of slow twitch (ST) fibres have a longer duration which favours muscle stiffness. If the ST fibres play a greater role to maintain the required tension level, as the fast twitch fibres become fatigued, the stiffness of the muscle would be further increased. The increased stiffness might partly offset the influence of the decreased rate of force development on EMD during fatigue. However, controversial evidence has been reported in the literature. Vigreux et al., (1980) have found that the compliance of elbow flexors increased under fatigue conditions, i.e. the muscle would be stretched to a greater degree and a longer time would be required to achieve a certain force level. Increased muscle temperature would also decrease muscle stiffness and therefore elongate EMD (Zhou et al., 1996). The effects of fatigue on EMD, due to the elasticity changes in either tendons or contractile proteins, needs further study. The current study clearly demonstrated an elongation of EMD with fatigue. It is likely that this reflected impaired contractile mechanisms, increased compliance of the SEC, with a reduction in muscle fibre conduction velocity.

In response to muscular fatigue, Rozzi et al., (1999) indicated that there was an overall decrease in the ability to detect joint motion moving into the direction of extension, and an increase in the onset time of contraction for the medial hamstring and lateral gastrocnemius muscles in response to a landing task. Muscular fatigue is considered an important factor in impaired neuromuscular mechanisms, as research has demonstrated its deleterious effects on knee joint laxity as well as both the afferent and efferent neuromuscular pathways (Ribeiro et al., 2007). A importance aspect of altered joint proprioception due to fatigue is a decrease in neuromuscular control (Rizzu et al., 2000). As a consequence of the increased latency periods during the fatigued state, muscles are not able to respond quickly enough to protect a joint from injury, especially in females. Alterations in the afferent input to the alpha motor neurons can potentially affect reactive muscular function and decrease the protection of the joints (Rizzu et al., 2000). Skinner et al., (1986) reported that during fatigue conditions participants had significantly decreased proprioceptive abilities. They hypothesized that this was due to either altered afferent impulses from the muscles themselves or from abnormal stresses in the joint capsule as a result of the muscle fatigue (Skinner et al., 1986). Altered joint proprioception due to fatigue may impact on neuromuscular control (Rizzu et al., 2000). Our findings support the view that the influence of fatigue on the EMD in hamstring muscles in females and males at all three angular velocities potentially influences dynamic muscular control of knee joint alignment, and that specifically differences in muscle recruitment and EMD may be partly responsible for the risk of ACL injury. Our findings of increased EMD with fatigue tentatively suggest that proprioception and joint control are altered when fatigue is present, due to decreased neuromuscular control. However, more studies are needed to explore the influence of fatigue on proprioception and knee joint position sense, which may alter landing mechanics, when individuals are fatigued.

A slowing of muscle fibre conduction velocity with fatigue has been calculated to contribute up to 15% of the prolongation of EMD (Zhou et al., 1996). Yeung et al., (1999) have shown a significant increase in EMD of the vastus medialis following 30 isometric maximal voluntary actions and Horita and Ishiko, (1987) have also found that the median frequency (MF) of the surface electromyogram (EMG) recorded from vastus lateralis was decreased while the time lag of torque production after the onset of electrical activity (EMD) was increased. However, it has to be noted that the results of the present study should be cautiously compared to the findings of other studies using different fatigue protocols, muscle groups, angular velocities, participants and positions of measurement.

Adult studies have also reported that sub-maximal fatigue not only increases anterior tibial translation but that this is accompanied by significantly longer latency of the hamstring muscles, subsequently decreasing joint stability (Melnyk and Gollhofer, 2007). Because of the increased latency periods during the fatigued state, muscles may not be able to respond quickly enough to protect a joint from injury. Considering this time lapse and the need to develop sufficient muscle tension rapidly enough to provide dynamic knee stability, and according to our findings, the EMD should be considered when evaluating muscular responses to an imposed perturbation or injurious stress.

7.5 Sex differences in response to fatigue on EMD

The findings of the present study (chapter 6) demonstrated statistically significant interactions between sex and time (pre-post) for EMD. In addition, a statistically significant interaction between sex and angular velocities was demonstrated. These findings indicate that the EMD in hamstring muscles of females at all angular velocities was longer post-fatigue compared to males and the sex difference in EMD post fatigue increased with increasing angular velocities. Percentage decline in the EMD of males ranged between 8 to 22% and 17 to 28% for females which confirms that the effect of fatigue on males and females is different as the EMD was lobger in females compared to males. However, as shown in study two (chapter 5), there were no sex differences in the EMD in hamstring muscles, irrespective of angular velocity when fatigue is not present. That which makes us refuses the hypothesis 11 which states that irrespective of sex or time, the EMD will be significantly different between hamstrings muscle groups. It would appear that latency periods in women are not different from men under normal conditions and therefore we would suggest that reduced neuromuscular functioning is not a contributing factor in the elevated relative risk of injury in females, when the muscles are not fatigued. The findings of current study are in agreement with previous literature (Houston et al., 1988, Blackburn et al., 2009, Winter and Brookes, 1991) that found no significantly different **EMD** values between females and males, albeit from different muscle groups and different muscle actions. It is well established that EMD can be relatively variable due to factors such as fibre-type composition and firing rate dynamics of the muscle, velocity of movement, viscoelastic properties and length of the muscle and tendon tissues, activity state, and coactivity of other muscles (De Luca, 1997, Soderberg and Cook, 1984). Our data suggest that these factors do not seem to be a contributing factor in terms of the relative risk of reduced dynamic knee stability from a neuromuscular perspective in females when fatigue is absent. However, the time required for the contractile component to stretch the series elastic component (SEC) probably accounts for the major portion of EMD, but how the elastic property affects EMD of males and females when fatigue is present is not clear.

The percentage changes in EMD with fatigue were accompanied by a marked lengthening in EMD in all hamstring muscles and were 25, 19, 30% in males and 41, 36, 37% in females at 60, 120 and 240°·s^{-1} respectively. Importantly the effect of fatigue was not similar in males and females at all three angular velocities. The finding in present study showed a significantly longer EMD post fatigue in females compared to males. This finding confirmed previous reports that have shown that the influence of fatigue on EMD differs between sexes (Moore et al., 2002, Minshull et al., 2007). These results suggest males and females may respond differently to fatigue, with males having a greater capacity to compensate for neuromuscular failure when responding to mechanical perturbations. However, it is difficult to compare our data to the extant literature as no previous studies have examined the effects of fatigue on the EMD in hamstring muscles in males and females during eccentric actions. The observed sex difference in the present study could be attributable to a number of mechanisms. It could represent differences in fibre type distribution (Viitasalo and Komi, 1981, Woledge et al., 1985), with type II fibres having shorter force-developing times than type I fibres. However, this may be unlikely as it has been proposed that systematic differences in fibre type attributable to sex do not occur (Nygaard, 1981). The work of Padua et al., (2006) demonstrated greater co-activation ratios in females compared to males in a fatigued state. It has also been reported that, there was an increase in EMD in women after fatiguing protocol, while no difference was observed in men (Moore et al., 2002). Moreover, in a study of Minshull et al., (2007) it was indicated that EMD increased post-fatigue in women and did not change in men when subjects voluntarily contracted their muscles, but it decreased at post-fatigue for both women and men when muscles were stimulated magnetically. Comparing our data with previous studies should be conducted with a degree of caution, as we measured EMD in the hamstring muscles during eccentric actions and in a prone position which is functionally relevant. Other studies have used a range of different protocols, muscle actions, muscle groups, angular velocities, participants and positions of measurement to determine EMD.

Very few studies have specifically addressed potential sex differences in neuromuscular response characteristics, especially when fatigue is present (Huston and Wojtys, 1996, Bell and Jacobs, 1986, Winter and Brookes, 1991). These studies have been interested primarily on muscle firing patterns during various functional manoeuvres. A study by Besier et al., (2003) determined that during running and cutting manoeuvres male participants exhibited significantly lower muscle activation during unanticipated conditions. This resulted in less stiffness in varus/valgus at the knee and internal/external rotation of the tibia, which could lead to less neuromuscular control of the knee joint (Besier et al., 2003). Moore et al., (2002) recorded vastus lateralis activity and knee extension force production at the distal tibia. They also found that, there was an increase in EMD during concentric muscle actions in women after (immediate, 2, 4, and 6 min) a concentric isokinetic fatigue protocol to 50% MVC (90°·s^{-1}), while no difference was observed in men. In addition, Minshull et al., (2007) indicated that EMD of the biceps femoris muscle increased post- acute maximal intensity fatiguing exercise in women and did not change in men during voluntarily isometric actions. Conflicting data are available and the findings of Yavuz et al., (2010) indicated that EMD of triceps surae muscle increased post-fatigue but no difference was observed between men and women. However, the EMD values in those studies were determined using different methods that may not have included the activation of all motor units in those muscles and hence precise duration of the EMD may have been over estimated. Although direct comparisons are difficult, due to the differences in study designs and protocols, muscle group examined and movement velocity. Notwithstanding these comparison challenges, our findings are similar to the limited extant literature. However the current study is the first to demonstrate these sex differences when fatigue is present across a range of movement velocities, during eccentric actions, in a functionally relevant position, and with a large sample size (n=100).

7.6 FH/Q ratio and influence of sex, angular velocity and joint angle

Females with decreased hamstrings relative to the quadriceps PT may be at increased risk of injury (Knapik et al., 1991). Therefore, the aim of the present study was to review the effects of sex, angular velocity and joint angle on the FH/Q ratio. The findings of study one (chapter 4) demonstrated that, a significant two-factor angular velocity (60, 120 and 240°·s-1) by sex (males; females) interaction, and angular velocity by knee joint angle interaction, associated with the repeated measures ANOVA showed that whereby, across angular velocity, FH/Q ratio was higher for males than females (Figure 11) this interaction also indicated that the FH/Q ratio increases closer to full knee extension with increasing angular velocity. However, there were no significant three-factor interactions, for angular velocity, joint angle and sex. Significant main effects for angular velocity were observed, for both males and females, whereby, FH/Q ratio increased with angular velocity. Those interaction indicated that the FH/Q ratio of males and females increases closer to full knee extension and was lower in females compared to males with increasing angular velocity. In addition, significant main effects for angular velocity and joint angle were observed. Whereby, for males and females the FH/Q ratio increases closer to full knee extension and also increases with increasing angular velocity. This is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles. The FH/Q ratio, outside the 0.7-1 range, when calculated near full knee extension (0^{o}) suggests an increase in the injury risk (Croix and Korff, 2011). The functional ratios below 1.0 in the current study may also be attributed to the inability of females to recruit their entire motor unit pool during eccentric actions. According to the current findings, injury occurrence in females is may be due to a specific hamstring weakness the FH/Q ratio and should decrease when approaching full knee extension and with increasing angular velocity. This would represent the inability of the hamstrings to absorb the anterior tibial forces induced by the concentric quadriceps action. This has implications for dynamic knee stability near full knee extension and reinforces the need to examine the ratio closer to full knee extension at increased angular velocity spatially in females. Therefore, that which makes us accepts the hypotheses 1,2 and 3 which states that the FH/Q ratio will be significantly lower in females compared to males and will significantly increase as velocity of movement increases and also ill significantly decrease with decreasing knee joint angle (closer to full knee extension).

The reduction in strength that was evidenced in the current study (chapter 4) by a decline in eccentric compared to concentric PT with increasing angular velocity is in agreements with the results of Costain and Williams, (1984) who measured the quadricep and hamstring torque levels of 16 high school soccer players using a Cybex II dynamometer at slow (0.54 $rad.s^{-1}$) and fast (3.24 $rad.s^{-1}$) velocities. They reported a significant decrease in PT in both muscle qroups from the slow to the fast velocity. In addition, Stafford and Grana, (1984) assessed the knee extensors and knee flexors of 60 intercollegiate soccer players at functional angular velocities of 1.62, 3.24 and 5.4 $rad.s^{-1}$ on the Cybex II and found the same results. In the previous observations also, it is well documented that the quadriceps muscle group possesses higher mean torque values (20-40 % greater) than the hamstrings irrespective of muscle actions (Goslin and Charteris, 1979, Wyatt and Edwards, 1981). Westing and Seger (1989) investigated the eccentric and concentric torque velocity characteristics of the quadriceps and hamstring muscle groups. They reported that mean concentric PT was significantly lower than the corresponding eccentric PT at all assessment velocities. However, they observed that mean eccentric torque did not change significantly with increasing angular velocity for either the quadriceps or hamstring muscles. Our results support those observations which have reported that the quadriceps posses' greater concentric torque than the eccentric hamstring muscles at all angular velocities. Hewett et al., (2008) showed a significant increase in the CH/Q ratio with increasing angular velocity, from the lowest (0.52$rad.s^{-1}$) compared to the highest velocity (6.28$rad.s^{-1}$). At slower testing velocities, no sex differences in isokinetic CH/Q ratio were observed in study of Hewett et al., (2008), however with increased knee flexion/extension angular velocities, approaching those that occur during sports activities, significantly greater CH/Q ratios were observed in male than female athletes. The findings of current study confirmed that significant main effects for angular velocity were observed for both males and females, whereby, FH/Q ratio increased with angular velocity irrespective of joint angle position with lower FH/Q ratio in females compared with males' at all three angular velocities. As velocity of motion increases during supine and prone position isokinetic activity, the forward momentum of the tibia increases to a point where increased hamstrings recruitment is required to limit both extension rotation and anterior translation of the joint. Consequently, as angular velocity increases, males and females increase their hamstrings to quadriceps PT output in order to stabilise the joint and protect the ACL (Hewett et al., 2008).

The manifestations of functional changes occurring are multiple and depend on the joint angle, angular velocity, action type (Green, 1997). Limited, research has been carried out to determine whether or not females and males respond to increased angular velocity and change in the angle-specific torque values with increased hamstrings torque relative to their quadriceps torque. In the current study, at deceased joint angles (closer to full knee extension) the FH/Q ratio at all three angular velocities was increased due to a larger decrease in the quadriceps concentric torque than in eccentric hamstrings torque. The stability systems are affected by changes in the joint angle, therefore observing the change in the angle-specific torque values may be relevant to knee stability as it describes the joint angle at which specific muscle action is most effective, however there are a limitation of using FH/Q ratio at angle-specific torque. The current findings that the FH/Q ratio increases with decreased joint angle have been reported by several investigators (Coombs et al., 2002, Aagaard et al., 1998, Kellis and Katis, 2007). These studies have determined torque in a seated position with the hip flexed at 90° which is not functionally relevant, but despite this our findings are consistent with the extant literature. Aagaard et al., (1998) used females and male track athletes to investigate joint angle-specific FH/Q ratio and found that maximal eccentric strength was greater than maximal concentric strength for both the quadriceps and hamstring muscles. In addition, maximal quadriceps muscle strength was elevated when obtained at gradually more flexed knee joint positions (i.e., 50°.40°.30°). Conversely, maximal hamstring muscle strength was greater when obtained at gradually more extended positions (i.e., 30°.40°.50°). Furthermore, the FH/Q ratios for fast knee extension (4.19 rad.s^{-1}) were 1.0, 1.1, and 1.4 based on 50°, 40°, and 30° moments, respectively and the corresponding values for slow knee extension (0.52 rad.s^{-1}) were 0.6, 0.8, and 1.0. Therefore, the FH/Q ratio was increased as we found in the current study with extended knee joint positions and with decreased joint angle at 0.52 rad.s^{-1} compared with 4.19rad.s^{-1}. However, they ignored joint angles lower than 30°, where dynamic stability is often challenged. Coombs and Garbutt, (2002) used 9 females and 6 males recreational athletes to calculate joint angle-specific FH/R ratio values throughout a 90° range of movement and found increasing FH/R ratio values especially at 10°. Eccentric or concentric angle specific torque prior to and following fatigue may partly explain the increased FH/Q ratio. The findings of the current study demonstrated that statistically significant three-factor interactions were observed between sex, angular velocity, joint angle (15º, 30º, 45º and PT) respectively for the FH/Q ratio and also significant main effects for joint angle were observed with greater FH/Q ratio closer to full knee extension. This is in agreements with study of Kellis and Katis, (2007) who found that FH/Q ratio significantly increased at 1.05 and 3.14rad.s^{-1} as the knee extended at increased angular velocity. As a result, landing that occurs with the knee angle greater than 30° of flexion places less load on the ACL compared to landing in more extended knee positions (Myers and Hawkins, 2010). For fast knee extension, the FH/Q ratio yielded a 1:1 relationship, which increased with extended joint angle position, indicating a significant capacity of the hamstring muscles to provide dynamic joint angle stability in these conditions. The data of current study support the literature indicating that functional stability is enhanced near full knee extension. Therefore, the evaluation of joint angle function by exercise of isokinetic dynamometry should comprise data on FH/Q ratios and to protect the knee joint, the FH/Q ratio should be higher at more extended knee positions.

For sex differences, analysis and review of isokinetic data published in the literature demonstrated significantly differences in FH/Q ratio between males and females (Calmels et al., 1997, Yoon et al., 1991, Hewett et al., 2008). The findings of current study support previous observations which have reported a higher FH/Q ratio in males compared with females. This may be due to the more powerful quadriceps muscles as compared to the hamstrings muscles in females or may be due to the greater efforts of the hamstrings of females than males in the control of running activities and for stabilizing the joint angle during foot contact with the ground or due to females maintaining lower eccentric torque compared with males. Other investigators, however, have reported a similar FH/Q ratio between sexs (Bojsen-Moller et al., 2007). Hewett et al., (2008) demonstrated no sex differences in isokinetic conventional H/Q ratio were observed at slower (0.52 $rad.s^{-1}$) testing velocities but, with increased knee flexion/extension angular velocities, approaching those that occur during sports activities, significantly greater conventional H/Q ratios were observed in male than female athletes. The disagreement concerning the effect of sex on FH/Q ratio may be related to use the different age ranges, different angular velocities and positions of measurement, small sample size and training background of participants.

The contribution of antagonists during particular phases of the movement is very important in many activities because the antagonists control and stabilize the joint when large forces are developed (Baratta et al., 1988, Patton and Mortensen, 1971, Kellis and Baltzopoulos, 1995). Co-activation of the hamstrings during active knee extension assists the ACL in maintaining joint angle stability by exerting an opposing force to anterior tibial translation (Baratta et al., 1988, Osternig et al., 1995). As a result, determination of the strength of the antagonists and its relationship to agonists has been extensively investigated (Kellis and Baltzopoulos, 1995). The issue of the change in the torque-velocity relationship after repeated eccentric actions has been observed by Brockett et al., (2001). Perrin, (1993) later stated that the force -velocity curve produced during eccentric exercise is quite different from the curve resulting from concentric muscular contraction. For instance, while concentric force decrease with increase in contraction velocity, eccentric force remains the same and sometimes even increases in force production are observed. This difference may be due to differences in the binding and interaction of actin and myosin within the muscle sarcomere.

ACL injury risk in female athletes is associated with the relatively low knee flexor to extensor ratio or hamstrings to quadriceps PT ratio (Hewett et al., 2006). Quadriceps contraction increases ACL strain in the first 30° to 45° of knee flexion, and isolated quadriceps contraction can create forces beyond those required for ACL tensile failure (Fleming et al., 2003, Lloyd, 2001, McNair et al., 1990, Myklebust et al., 1998). Arms et al., (1984) confirmed that ACL strain increased to 45° of flexion and decreased at knee flexion angles greater than 60°. Beynnon et al., (1992) reported that the ACL was strained by quadriceps contraction at 30° but not at 90° using in vivo techniques. They also reported that quadriceps contraction significantly increased at 15° and 30° but decreased at

60° (Beynnon et al., 1995). Hewett et al., (2006) believed that co-activation of the hamstrings and quadriceps muscles may protect the knee joint not only against excessive anterior drawer, but also against knee abduction and dynamic lower extremity valgus. If the hamstrings are weak, quadriceps activation would have to be reduced to provide a net flexor moment required to perform the movement (Hewett et al., 2005, Hewett et al., 1996). Shortage in strength and activation of the hamstrings directly limit the potential for muscular co-contraction to protect ligaments (Solomonow et al., 1987). Co-contraction of the knee flexors is essential to balance active contraction of the quadriceps in order to compress the joint and assist in the control of high knee abduction torques and anterior tibial translation (Solomonow et al., 1987). The observations of our study further support suggestions that FH/Q ratio is more suitable to recognise the ability of the knee flexors in stabilising the joint than angle the conventional ratio. This is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles. This is due to the lower maximal capacity of the hamstrings compared to the quadriceps. The findings of the current study showed a significant increase in the FH/Q ratio closer to full knee extension and with increased angular velocity. This is due to the relatively greater reduction in eccentric vs. concentric torque production. These findings are in agreement with previous studies. However, this is the first study to have explored these effects in a functionally relevant position (e.g. prone) and exploring angle specific torque as well as a range of movement velocities.

7.7 EMD and influence of sex, angular velocity and hamstrings muscle group

The main findings of present study demonstrated significant main effects for angular velocity, indicating an increase in the EMD in all hamstring muscles with increasing angular velocity, irrespective of sex or time. That which makes us accepts the hypothesis 5 which states that the EMD will be significantly longer as velocity of movement increases. However, no significant main effects for hamstring muscles or sex were observed at all three angular velocities. That which makes us refuses the hypotheses 4 and 6 which states that the EMD will be significantly longer in females compared to males and the EMD will be significantly different between hamstrings muscle groups. These results suggest that neuromuscular functioning of the hamstring muscles, with increasing angular velocity, is reduced and may limit dynamic knee joint stability, potentially contributing to the greater ACL injury risk. It has previously been suggested that EMD will vary substantially due to the characteristics of the muscles being tested (e.g. architectural arrangement and fibre type distribution) (Viitasalo and Komi, 1981); muscle action (e.g. eccentric, concentric, voluntary, reflexive) (Norman and Komi, 1979, Zhou et al., 1995); and data processing techniques (Corcos et al., 1992). However, a limited number of studies have investigated the influence of movement velocity on EMD, and only one during eccentric actions. This is surprising given the range of movement velocities produced during sporting performance and that non-contact ACL injury may be velocity dependent.

Understanding the influence of fatigue on the EMD during different velocity movements is important as EMD is a component of the reflex time, which is important as it affects muscle response to sudden movements during athletic activities. The effect of movement velocity on motor unit recruitment strategies during isokinetic testing was studied by Ronald et al., (1998) between 1.05, 3.14 and 4.19 rad.s^{-1} and elucidated that there is no change in the motor units recruited for the quadriceps, however there is a general upward shift for the hamstrings as velocity increases indicating an increased recruitment of the fast twitch motor units. Additionally, as the quadriceps and hamstrings fatigue during isokinetic movements, there is a general shifting of the median frequency of the electromyographic activity toward the lower frequency demonstrating a change in recruitment from the fast twitch to slow twitch motor units. The current study showed a significant main effect for angular velocity, indicating an increase in the EMD in hamstring muscles with increasing angular velocity. The study of Barnes, (1980) suggested that the decline in torque output due to increasing angular velocity is a result of different neurological activation patterns of motor units at different velocities.

When EMD measures are collected on more than one muscle group, activation patterns such as recruitment order and coactivity around a joint can also be evaluated. In the current study no differences were found between the EMD of all hamstring muscles, irrespective of sex or if fatigue was present, suggesting that the speed in which the hamstrings investigated activate during eccentric actions are similar, and thus all of the active muscles are equally contributing to the stabalisation of the joint from a neuromuscular perspective. These data agree with the previous findings of Georgoulis et al., (2005) who found no significant differences for the EMD for either the rectus femoris (RF) or the vastus medialis (VM) muscle during maximal isometric voluntary action.

The changes of the EMD might play an important role in the organization of the movement and probably result in impairment of neuromuscular control, through its relationship with the reflex time. The current findings showed a significant main effect for time, indicating that the EMD in hamstring muscles was longer post-fatigue compared to pre-fatigue. In addition, significantly longer EMD in females compared to males was found post fatigue, but there were no sex differences in the EMD of hamstrings muscle at all three angular velocities pre fatigue. These results suggest that the EMD is slower in both males and females due to the change to an ankle dominant rather than knee dominant strategy to protect the knee on landing. This might be why EMD around the knee muscles is reduced as they rely more on the muscles that support the ankle. The prolongation of the EMD during fatigue may be largely attributed to the failure of the muscle contractile process. These results suggest that neuromuscular hamstring function following downhill running fatigue may limit dynamic knee joint stability, potentially contributing to the greater ACL injury risk. This finding confirmed previous reports that have shown that the influence of fatigue on EMD differs between sex (Moore et al., 2002, Minshull et al., 2007). These findings are in agreement with previous studies and suggest that males and females respond differently to fatigue, with males having a greater capacity to compensate for neuromuscular failure when responding to mechanical perturbations. However, no previous studies have examined the effects of fatigue on the EMD throughout hamstring muscles in males and females during eccentric actions. Therefore, this is the first study to have explored these effects in a functionally relevant position (e.g. prone with the hip extended) as well as a range of movement velocities.

The differential changes in EMDv performance between sexes in the current study could be partially explained by a generally greater compliance in biologic tissue in females (Wojtys et al., 1998), exacerbated by muscle temperature increases associated with the fatiguing exercise (Zhou et al., 1998). Given the many injury risk factors experienced by females, habituated exposure to scenarios where knee joint stability may be under threat might condition the neuromuscular system of the healthy female athlete at functional joint angles. The subsequent formation of pre-programmed responses that provide fast compensatory reactions to joint perturbations (Latash, 1998) may quickly harness the SEC and account for the parity in EMDV performance observed between the sexes at baseline. Under conditions of muscle fatigue and sustained loading, however, this capability may be diminished due to a reduction of the effectiveness of the fastest most powerful motor units, impairing the temporal capability of the muscle to 'gather in' a more compliant SEC.

7.8 Implications for practice

The focus of the present research is a result of the documented sex disparities in dynamic knee stability from a muscular and neuromuscular perspective and potential influence of fatigue. The findings of the present study demonstrated that FH/Q ratio was lower in females than males both pre and post fatigue. This is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles. However, the significant sex differences increased when fatigue was present. The existing evidence of greater prevalence of muscle imbalances among female than male athletes is now supplemented by the findings of the present series of studies suggesting that the FH/Q ratio may be a key factor for ACL tears and hamstrings muscle strains (Moeller and Lamb, 1997, Hewett et al., 1999, Huston and Wojtys, 1996). Males also demonstrated a significant decrease in FH/Q ratio with fatigue post exercise and fatigue is known to be related to incidence of ACL injury. Therefore, the present study's findings lead to a recommendation that females, in particular, should do eccentric training of their hamstring muscles that may alter the rate of force production to hopefully increase dynamic knee stability.

Narici et al., (1996) also reported a significant decrease in time to peak isometric torque of quadriceps muscle after strength training on knee extensors. They suggested that this observation could indicate an increase in the stiffness of the muscle-tendon complex after training. Furthermore, as suggested by Wilson et al., (1994) an increase in the stiffness of the muscle-tendon complex should result in a higher force and rate of force development. Interestingly a recent study of De Ste Croix and Korff, (2011) on adults suggests that heavy intensity aerobic training reduces the FH/Q ratio.

The deficits in strength and insufficient activation of the hamstrings limit the potential for muscular co-contraction to protect ligaments (Hewett et al., 2008). The findings of the present study revealed significant sex differences in EMD of hamstrings muscle; however this finding that demonstrated longer EMD in females compared with males was only evident post fatigue and no sex differences were found pre fatigue. EMD of males was also longer post fatigue than pre fatigue. Theoretically, any factors that influence muscle fibre conductivity, contractility, or elasticity may alter EMD. The effects of fatigue on EMD can be attributed to peripheral processes and not to central fatigue or neuromuscular transmission failure. The current study’s finding would suggest that neuromuscular hamstring function in females with fatigue may limit dynamic knee joint stability, potentially contributing to the greater female ACL injury risk. Indeed, the current results may provide a new insight into the complex phenomenon that describes a fivefold to sevenfold increase risk of ACL injury in the female athlete compared to male counterparts. Considering lapse time and the need to develop sufficient muscle tension rapidly enough to provide dynamic knee stability, EMD should be considered when evaluating muscular responses to an imposed perturbation or injurious stress. The effect of training on the neuromuscular performance has previously been studied. The majority of available data clearly indicates that training that has an effect on neuromuscular performance appears to reduce the relative risk of injury and enhance physical performance.

The effects of training on the neuromuscular performance have previously been studied and findings are conflicting. Increased muscle activation levels in the triceps surae after 12 weeks of plyometric training were found by the twitch interpolation technique (Kubo et al., 2007) and Grosset et al. (2011) have assessed maximal aerobic velocity during endurance training and have shown that endurance training leads to a significant decrease in EMD. In addition, Kubo et al., (2001) reported a decrease in EMD after isometric training, but Zhou et al. (1996) found no changes in EMD following sprint training. Similarly Hakkinen and Komi, (1983) reported no significant differences in EMD values calculated under reflex contraction before and after 16 weeks of strength training. For healthy adults, data reported in the literature indicate that, for the hamstrings muscle, the EMD value obtained from maximal electrical nerve stimulation are generally between 9.5 and 18.7 ms (Grosset et al., 2011, Mora et al., 2003, Winter and Brookes, 1991). Those authors who reported changes in the EMD with training mainly attributed this change to alterations in tendon structures; the stiffness of the tendon is assumed to increase with any form of physical activity. Therefore, the present study’s findings lead to a recommendation that females, in particular, should do training to increase fatigue resistance for neuromuscular function.

A direct association between the EMD and musculo-tendinous stiffness changes after a training period have been demonstrated by Grosset et al., (2011). Furthermore, the changes in elastic properties due to training have been well documented; Goubel and Marini, (1987) reported that endurance training resulted in an increase in the series elastic component stiffness in the soleus muscle, associated with an increase in type I fibres. Both jump and endurance training also appear to increase both collagen concentration (Ducomps et al., 2003, Kovanen et al., 1980) and muscle passive stiffness. The soleus muscles submitted to plyometric training had faster twitch fibres and lower series elastic component stiffness than controls (Almeida-Silveira et al., 1994, Pousson et al., 1991, Watt et al., 1982). Malisoux et al. (2006) recently reported that human subjects given 8 weeks of maximal effort stretch-shortening cycle exercise training tended to have an increase in the proportion of type II fibres in their vastus lateralis muscles. Therefore, in response to the findings of the present study it is recommended that, especially in females, eccentric training should be conducted to improve the neuromuscular performance and to hopefully reduce the relative risk of injury.

Irrespective of sex or time, the current study demonstrated significant main effects for angular velocity were found, indicating an increase in the FH/Q ratio and longer EMD of hamstring muscles with increasing angular velocity. Therefore, the observations of the current study further support suggestions that joint velocity needs to be considered when training hamstrings muscles. The present study's findings lead to recommendations that males and females should do eccentric training for their hamstring muscles to increase dynamic knee stability especially at higher angular velocity. Furthermore, the focus should be on neuromuscular functioning as EMD is longer at faster velocities. The results from Brockett et al., (2001) study reported muscle adaptation after a single bout of eccentric exercise incorporating the Nordic Hamstring Exercise (NHE) represented by a shift in PT production to longer muscle lengths. Therefore, a prior bout of eccentric training may provide protection against more severe damage in a subsequent activity which possesses different force-velocity characteristics. Further to this, training with the NHE appears not to result in velocity specific adaptations, which implies that training at a slow angular velocity (i.e., the NHE) could provide protection against injuries that occur during sporting activities like running where angular velocity can reach in excess of $300°\cdot s^{-1}$ (Knapik et al., 1991). In addition, the study of De Ste Croix et al., (2009b) demonstrated significant increases in eccentric hamstring strength after only four weeks of training incorporating the NHE and also demonstrated that training with the NHE at slower angular velocities does not result in velocity specific adaptation, as increases, in eccentric hamstrings strength were recorded at much faster angular velocities. This would suggest that the NHE could be included as part of pre season training modality to provide protection against hamstring strains.

Irrespective of sex or time, the main findings of the present study demonstrate significant main effects for joint angle indicating that there were increases in the FH/Q ratio with decreasing joint angle (closer to full knee extension). Importantly the effect of joint angle differed in magnitude in males and females where significantly lower FH/Q ratio in females was found compared to males especially when fatigue is present and at decreasing joint angle (closer to full knee extension). This suggests that the decrease in the ratio was greater at more extended knee positions. This has implications for dynamic knee stability near full knee extension and reinforces the need to examine the ratio closer to full knee extension, especially in the fatigue condition. Therefore, training programmes should develop strength through the full range of knee joint motion, especially when fatigue is present. However, recommendations supported by evidence are not possible, since no studies appear to have explored the influence of strength training on angle specific torque near full knee extension.

Finally, the present findings highlight the importance of joint angle, angular velocity and action-specificity when calculating the FH/Q ratio. It has been found that ACL rupture is most likely to occur near full knee extension during a high velocity movement in both males and females. The FH/Q ratio, when calculated near full knee extension (0º), suggests an increase in the injury risk. If it is to be accepted that injury occurrence is due to a specific hamstring weakness, the FH/Q ratio should decrease when approaching full knee extension and with increasing angular velocity or in the presence of action-specific fatigue. This would represent the inability of the hamstrings to absorb the anterior tibial forces induced by the concentric quadriceps action. In addition, all of the available adult studies seem to show a significant increase in EMD after fatiguing trials and with increased angular velocity which would predispose the knee to greater injury risk. Therefore, in summary, any training which increases resistance to fatigue in terms of FH/Q or EMD should be advocated. Such training should focus on high velocity near full extension exercises. Such training is particularly important in females.

7.9 Implications for further research

The present research that forms the basis for this thesis has been designed to answer highly focused research questions. The answers to these questions, along with the absence of answers to many related questions, provides a basis for further research to develop a greater level of understanding in this important area.

It is well recognised in adults that fatigue affects eccentric and concentric actions differently and that generally eccentric actions are more fatigue resistant than concentric actions. Therefore, in a fatigued state the FH/Q ratio should increase and the knee should be more stable. The present findings have confirmed that this is not the case following a fatigue intervention that worked the lower limbs eccentrically so, given the practical importance of the present findings, future research should confirm whether the findings may be replicated following other fatiguing interventions. The answers provided would be equally as interesting from the perspective of the EMD outcome, since further information is required regarding the extent of the influence of the type of exercise (i.e., eccentric).

The extensive literature has documented the effects of varying degrees of eccentric exercise and its role in inducing muscle fatigue. However, the issue observed in the literature is that the fatigue protocols used are not ecologically valid in that they only address one of the components of team games. Overall duration or maximum intensity efforts are considered but team games are characterised by the alternation of high and low intensity efforts during an extended period of time. Therefore, although interventions induced fatigue, it appears necessary to develop a downhill running protocol that has a similar effect to the games situation to be even more ecologically valid.

The downhill running protocol that was used in the present study could be manipulated to vary gradient, interval length, and total duration. Such manipulations could be used to determine the extent of the 'mechanical' (as opposed to the metabolic) influence of the eccentric exercise on the outcomes.

It is recommended that further research should explore the validity and reliability of the most common techniques used to measure muscle function of the knee in different populations (asymptomatic athletes, injured athletes, elderly) using several testing sessions and positions (seated, standing, supine). Also, outcome measures in the current study should be confirmed with altered aspects of the procedures (e.g., supine posture versus sitting) to determine more completely how the present findings contrast with previous findings, and the potential methodological reasons for any differences.

A further methodological variable is the duration of the gap between the end of the fatiguing intervention and the start of post-testing, and future research in this area should determine how short-term or persistent the fatigue effect was. Such research may have benefits in determining both the physiological basis for the fatigue (e.g., metabolic or mechanical origins) as well as the practical implications in terms of post-training session fatigue and necessary recovery before subsequent training.

For a more detailed analysis of the effect of stretching on dynamic knee stability and its relationship with sport injuries, researchers should carrying out studies that investigate the mediating effect of stretching on fatigue and hamstring and quadriceps stiffness. Once again, the mediating effect of stretching may shed further light on the physiological basis of the fatigue effect. For example, a dominant mechanical (as opposed to metabolic) basis would be likely influenced to a greater degree by a stretching intervention during the course of a fatiguing trial.

The functional ratio pre and post fatigue was assessed in the present research through the large muscle groups involved. However, assessment of FH/Q ratio (pre and post fatigue) of upper body muscle groups may provide us with confirmation of sex differences where factors such as muscle training status may be less influential.

The change in FH/Q ratio and EMD of males and females should also be investigated pre-post fatigue interventions where likely mediating factors are manipulated to provide further insight into the physiological basis for the findings. The potential mediating influence of stretching has already been mentioned given the eccentric focus of the fatigue intervention in the present study, but other mediating factors could include: glycogen depletion, dehydration, heat stress, and footwear. All the aforementioned potential mediators might shed light on the physiological basis for fatigue effects on both FH/Q ratio and EMD.

Female athletes are known to have a higher risk of injuring their ACL while participating in competitive sports (Good et al., 1991). Unfortunately, to date, understanding why women are more prone to ACL injury is unclear. Therefore, it would be beneficial to determine whether hormonal status in females mediates the responses (i.e., pre-post changes in key outcomes) to a fatigue protocol. For example, a study could focus on fatigue in females (i.e., replicate the female arm of the present study).

Studies should also address sex differences in intrinsic stiffening responses and delays in force production not accounted for in EMG measures alone. In order for the neuromuscular system to be effective in preventing ligament strain, muscular tension must be developed in a timely fashion to limit joint deformation.

Intrinsic, mechanical properties within the muscle may differ between males and females, with males having the ability to initiate a more immediate stiffening response after muscular activation (Winter and Brookes, 1991). However, the relevance of these findings to the knee musculature is not known. Furthermore, these studies evaluated muscular response characteristics under voluntary conditions with the muscle at rest before the stimulus. These conditions are not representative of the dynamic and reflexive responses that may occur with joint perturbations or during sport activity, where the muscle may already be contracting. Research models assessing sex differences in reflexive stiffening and EMD at the knee under dynamic conditions and after unexpected joint perturbations are needed.

The time required for the contractile component of the knee extensor muscles to stretch the series elastic components probably amounts for the major portion of the EMD, but it is not well defined how the elastic properties affect the EMD. So, further research to confirm the physiological and anatomical basis for a lengthened EMD, and therefore allowing interpretion of the full implications of the EMD findings in the present study, is difficult. However, future research is necessary to establish the clinical/ physiological implications of heightened hamstring musculotendinous stiffness and the associated influences on neuromechanical function, as well as the ability to modify these neuromechanical properties via training.

The potential confounding influence of training status needs consideration when exploring potential sex differences in neuromuscular response characteristics. The different skill and training backgrounds required for various sport activities could potentially confound results, making it difficult to determine whether differences were due to sex or training status. Future studies should attempt to assess sex differences while controlling for skill level and training status across subjects.

Focus of studies should be on outcomes near full knee extension and the calculation of the FH/Q should be joint angle- and angular velocity-specific. This is important, since the present research showed the interactions between sex and time (fatigue) to be mediated by joint angle and angular velocity. No studies appear to have explored the influence of strength training on angle specific torque near full knee extension so more studies in this area are needed.

This is still an exploratory research area, so further research is needed to enhance the injury risk evidence base. Much of that research should build on the original and significant findings of the present studies. However, further research should also induce fatigue using different exercise modalities and with increased ecological validity.

Chapter 8:

CONCLUSIONS

The research questions presented in chapter 1 have been addressed through three experimental studies included within this thesis (chapter 4-6). The main aim of the thesis was to explore sex differences in the outcomes of FH/Q ratio and EMD prior to and following a downhill running fatigue task. The main findings of the present thesis showed a significant decrease in the FH/Q ratio and longer EMD of hamstrings muscle when fatigue is present, irrespective of sex. The decrease in FH/Q ratio is a result of reduced eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles when fatigue is present. These findings suggest that functional stability of the knee is compromised when fatigue is evident, in particular that neuromuscular hamstring function following downhill running fatigue may limit dynamic knee joint stability which might be cause for increased relative risk of injury.

Based on the limited literature it appears that this is the first study to have explored the effects of fatigue on the FH/Q ratio in a functionally relevant position (e.g. prone/supine with the hip extended) and exploring angle specific torque as well as a range of movement velocities in males and females. Importantly, the current body of work demonstrated that the effects of fatigue were more pronounced in females compared with males. The findings showed a significantly lower FH/Q ratio and significantly longer EMD post fatigue in females compared to males. Additionally, irrespective of time, significant main effects for sex were demonstrated, indicating that the FH/Q ratio was lower in females compared to males at each time point, but the differences increased post fatigue. However, there were no sex differences in the EMD pre fatigue at all three angular velocities. These sex differences may be due to the greater effort required by the hamstrings of females than males in the control of running activities and for stabilizing the joint during foot contact with the ground. If so, then this decline in females perhaps leads to less control and lower stability of the knee when fatigue is present and thus leads to a greater relative risk of injury.

Irrespective of time or sex, these studies have shown that as angular velocity increases the FH/Q ratio increases, with longer EMD during eccentric actions. This is attributed to males and females increasing their eccentric hamstrings to concentric quadriceps torque output in order to stabilise the joint and protect the ACL during fast movements. Sex differences increase as movement velocity increases and thus the dynamic knee stability is more compromised in females during fast velocity movements. Additionally, irrespective of time or sex the FH/Q ratio was significantly greater at more extended knee positions (e.g., closer to voluntary full knee extension). To protect the knee, eccentric hamstring co-contraction is greater at more extended knee positions to counteract the shear forces generated by the concentric quadriceps action. No studies have previously explored the change in the angle-specific FH/Q ratio following downhill running fatigue, but the findings of the current work reinforce its relevance to knee stability as it describes the joint angle at which injury is most likely to occur, and indicates that the applied muscle action is effective in limiting both extension rotation and anterior translation of the joint. This is especially important as velocity of motion increases, and the forward momentum of the tibia increases to a point where increased hamstrings recruitment is required. Therefore, as angular velocity increases, as shown in the present thesis, males and females increase their FH/Q ratio in order to stabilise the joint and protect the ACL.

It is well recognised in adults that fatigue affects eccentric and concentric actions differently, and that generally eccentric actions are more fatigue resistant than concentric actions. Therefore, in a fatigued state the FH/Q ratio should increase and the knee should be more stable. The present findings have confirmed that this is not the case following a fatigue intervention that worked the lower limbs eccentrically so, given the practical importance of the present findings, future research should confirm whether the findings may be replicated following other fatiguing interventions. The answers provided would be equally as interesting from the perspective of the EMD outcome, since further information is required regarding the extent of the influence of the type of exercise (i.e., eccentric). The change in FH/Q ratio and EMD of males and females should also be investigated pre-post fatigue interventions where likely mediating factors are manipulated to provide further insight into the physiological basis for the findings. For example, the potential mediating influence of stretching has already been mentioned given the eccentric focus of the fatigue intervention in the present study. Experimental manipulation of such potential mediators might shed light on the physiological basis for fatigue effects on both FH/Q ratio and EMD.

REFERENCES

APPENDICIES

REFERENCES

AAGAARD, P., SIMONSEN, E. B., ANDERSEN, J. L., MAGNUSSON, S. P., BOJSEN-MOLLER, F. & DYHRE-POULSEN, P. 2000. Antagonist muscle coactivation during isokinetic knee extension. / Coactivation du muscle antagoniste pendant une extension isocinetique du genou. *Scandinavian Journal of Medicine & Science in Sports,* 10**,** 58-67.

AAGAARD, P., SIMONSEN, E. B., MAGNUSSON, S. P., LARSSON, B. & DYHRE-POULSEN, P. 1998. A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *Am J Sports Med,* 26**,** 231-7.

AAGAARD, P., SIMONSEN, E. B., TROLLE, M., BANGSBO, J. & KLAUSEN, K. 1995. Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. *Acta Physiol Scand,* 154**,** 421-7.

AAGAARD, P., SIMONSEN, E. B., TROLLE, M., BANGSBO, J. & KLAUSEN, K. 1996. Specificity of training velocity and training load on gains in isokinetic knee joint strength. *Acta Physiologica Scandinavica,* 156**,** 123-129.

AARAS, A., VEIEROD, M. B., LARSEN, S., ORTENGREN, R. & RO, O. 1996. Reproducibility and stability of normalized EMG measurements on musculus trapezius. *Ergonomics,* 39**,** 171-85.

ABBOTT, B. C., BIGLAND, B. & RITCHIE, J. M. 1952. The physiological cost of negative work. *J Physiol,* 117**,** 380-90.

AGEL, J., ARENDT, E. A. & BERSHADSKY, B. 2005. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med,* 33**,** 524-30.

AGRE, J. C. & BAXTER, T. L. 1987. Musculoskeletal profile of male collegiate soccer players. *Archives of Physical Medicine & Rehabilitation,* 68**,** 147-150.

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.

ALBERT, M. 1983. Descriptive three year data study of outdoor and indoor professional soccer injuries. *Athletic Training,* 18**,** 218-220.

ALBERT, M. 1995. *Physiologic and clinical principles of eccentric. In: Eccentric Muscle Training in Sports and Orthopedics*, In: Eccentric Muscle Training in Sports and Orthopedics (ed.M. Albert). Churchill Livingstone, London, pp. 23-35.

ALBRIGHT, J., POWELL, J. W., SMITH, W., MARTINDALE, A., CROWLEY, E., MONROE, J., MILLER, D., HELWIG, D., MARSHALL, J., CONNOLLY, J. & HILL, B. A. 1994. Medial collateral ligament knee sprains in college football: effectiveness of preventive braces. *American Journal of Sports Medicine,* 21**,** 12-18.

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

ALLISON, G. T. 2003. Trunk muscle onset detection technique for EMG signals with ECG artefact. *J Electromyogr Kinesiol,* 13**,** 209-16.

ALMEIDA-SILVEIRA, M. I., PEROT, C., POUSSON, M. & GOUBEL, F. 1994. Effects of stretch-shortening cycle training on mechanical properties and fibre type transition in the rat soleus muscle. *Pflugers Arch,* 427**,** 289-94.

ALMOSNINO, S., PELLAND, L., PEDLOW, S. V. & STEVENSON, J. M. 2009. Between-day reliability of electromechanical delay of selected neck muscles during performance of maximal isometric efforts. *Sports Med Arthrosc Rehabil Ther Technol,* 1**,** 22.

AMIRIDIS, I. G., MARTIN, A., MORLON, B., MARTIN, L., COMETTI, G., POUSSON, M. & VAN HOECKE, J. 1996. Co-activation and tension-regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. *Eur J Appl Physiol Occup Physiol,* 73**,** 149-56.

ANDREWS, J. R. & AXE, M. J. 1985. The classification of knee ligament instability. *Orthop Clin North Am,* 16**,** 69-82.

ARENDT-NIELSEN, L., GANTCHEV, N. & SINKJAER, T. 1992. The influence of muscle length on muscle fibre conduction velocity and development of muscle fatigue. *Electroencephalography and Clinical Neurophysiology,* 85**,** 166-172.

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.

ARENDT, E. A. & AGEL, J. 1999. Anterior Cruciate Ligament Injury Patterns Among Collegiate Men and Women. *Journal of Athletic Training,* 34**,** 86.

ARMS, S. W., POPE, M. H., JOHNSON, R. J., FISCHER, R. A., ARVIDSSON, I. & ERIKSSON, E. 1984. The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *Am J Sports Med,* 12**,** 8-18.

ARMSTRONG, R. B. 1984. Mechanisms of exercise-induced delayed onset muscular soreness: a brief review. *Med Sci Sports Exerc,* 16**,** 529-38.

ARNDT, A., EKENMAN, I., WESTBLAD, P. & LUNDBERG, A. 2002. Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *J Biomech,* 35**,** 621-8.

ASAI, H. & AOKI, J. 1996. Force development of dynamic and static contractions in children and adults. *Int J Sports Med,* 17**,** 170-4.

AURA, O. & KOMI, P. 1987. Effects of Muscle Fiber Distribution on the Mechanical Efficiency of Human Locomotion*. *International Journal of Sports Medicine,* 8**,** S30-S37.

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

BAKER, A. J., KOSTOV, K. G., MILLER, R. G. & WEINER, M. W. 1993. Slow force recovery after long-duration exercise: metabolic and activation factors in muscle fatigue. *J Appl Physiol,* 74**,** 2294-300.

BALL, N. & SCURR, J. 2010. An assessment of the reliability and standardisation of tests used to elicit reference muscular actions for electromyographical normalisation. *J Electromyogr Kinesiol,* 20**,** 81-8.

BALTZOPOULOS, V. & BRODIE, D. A. 1989. Isokinetic dynamometry. Applications and limitations. *Sports Med,* 8**,** 101-16.

BANGSBO, J. 1994. The physiology of soccer--with special reference to intense intermittent exercise. *Acta Physiol Scand Suppl,* 619**,** 1-155.

BANGSBO, J., MARCELLO LAIA, F. & KRUSTRUP, P. 2007. Metabolic Response and Fatigue in Soccer. *International Journal of Sports Physiology & Performance,* 2**,** 111-127.

BARATTA, R., SOLOMONOW, M., ZHOU, B. H., LETSON, D., CHUINARD, R. & D'AMBROSIA, R. 1988. Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. / Coactivation musculaire: role des antagonistes dans le maintien de la stabilite du genou. *American Journal of Sports Medicine,* 16**,** 113-122.

BARNES, W. S. 1980. The relationship of Motor-unit activation to isokinetic muscular contraction at different contractile velocities. *Phys Ther,* 60**,** 1152-8.

BARRACK, R. L., SKINNER, H. B. & BUCKLEY, S. L. 1989. Proprioception in the anterior cruciate deficient knee. / Proprioception du ligament croise antero-externe du genou pathologique. *American Journal of Sports Medicine,* 17**,** 1-6.

BASMAJIAN, J. V. & DE LUCA, C. J. 1985. *Muscle Alive*: Their Functions Revealed by Electromyography. Baltimore: Williams and Wilkins.

BELL, D. G. & JACOBS, I. 1986. Electro-mechanical response times and rate of force development in males and females. *Med Sci Sports Exerc,* 18**,** 31-6.

BENNETT, J. G. & STAUBER, W. T. 1986. Evaluation and treatment of anterior knee pain using eccentric exercise. *Med Sci Sports Exerc,* 18**,** 526-30.

BEQUET, F., GOMEZ-MERINO, D., BERTHELOT, M. & GUEZENNEC, C. Y. 2002. Evidence that brain glucose availability influences exercise-enhanced extracellular 5-HT level in hippocampus: a microdialysis study in exercising rats. *Acta Physiol Scand,* 176**,** 65-9.

BERNS, G. S., HULL, M. L. & PATTERSON, H. A. 1992. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res,* 10**,** 167-76.

BESIER, T. F., LLOYD, D. G. & ACKLAND, T. R. 2003. Muscle activation strategies at the knee during running and cutting maneuvers. / Strategies d ' activation musculaire du genou lors de la course ou d ' autres deplacements. *Medicine & Science in Sports & Exercise,* 35**,** 119-127.

BESIER, T. F., LLOYD, D. G., COCHRANE, J. L. & ACKLAND, T. R. 2001. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc,* 33**,** 1168-75.

BEYNNON, B., HOWE, J. G., POPE, M. H., JOHNSON, R. J. & FLEMING, B. C. 1992. The measurement of anterior cruciate ligament strain in vivo. *Int Orthop,* 16**,** 1-12.

BEYNNON, B. D., FLEMING, B. C., JOHNSON, R. J., NICHOLS, C. E., RENSTROM, P. A. & POPE, M. H. 1995. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med,* 23**,** 24-34.

BEYNNON, B. D. & JOHNSON, R. J. 1996. Anterior cruciate ligament injury rehabilitation in athletes. Biomechanical considerations. *Sports Med,* 22**,** 54-64.

BIGLAND-RITCHIE, B. & WOODS, J. J. 1984. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve,* 7**,** 691-9.

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

BLACKBURN, J. T., DAVID, R. B., MARC, F. N., JEFF, D. H. & LAUREN, A. E. 2009. Comparison of hamstring neuromechanical properties between healthy males and females and the influence of musculotendinous stiffness. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology,* 19**,** e362-e369.

BODEN, B. P., DEAN, G. S., FEAGIN, J. A., JR. & GARRETT, W. E., JR. 2000. Mechanisms of anterior cruciate ligament injury. *Orthopedics,* 23**,** 573-8.

BOERBOOM, A. L., HUIZINGA, M. R., KAAN, W. A., STEWART, R. E., HOF, A. L., BULSTRA, S. K. & DIERCKS, R. L. 2008. Validation of a method to measure the proprioception of the knee. *Gait & Posture,* 28**,** 610-614.

BOJSEN-MOLLER, J., LARSSON, B., MAGNUSSON, S. P. & AAGAARD, P. 2007. Yacht type and crew-specific differences in anthropometric, aerobic capacity, and muscle strength parameters among international Olympic class sailors. *J Sports Sci,* 25**,** 1117-28.

BOOTH, F. W. & TIPTON, C. M. 1970. Ligamentous strength measurements in pre-pubescent and pubescent rats. *Growth,* 34**,** 177-85.

BROCKETT, C. L., MORGAN, D. L. & PROSKE, U. 2001. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Med Sci Sports Exerc,* 33**,** 783-90.

BROWN, L. E. & WEIR, J. P. 2001. ASEP PROCEDURES RECOMMENDATION I: ACCURATE ASSESSMENT OF MUSCULAR STRENGTH AND POWER. *Journal of Exercise Physiology Online,* 4**,** 1-21.

BUCHANAN, C. I. & MARSH, R. L. 2001. Effects of long-term exercise on the biomechanical properties of the Achilles tendon of guinea fowl. *J Appl Physiol,* 90**,** 164-71.
BURDETT, R. & VANSWEARINGEN, J. 1987. Reliability of lsokinetic Muscle Endurance Tests. *J Orthop Sports Phys Ther,* 8**,** 484-8.
BYRNE, C. & ESTON, R. 2002. The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Sciences,* 20**,** 417-425.
CADY, E. B., JONES, D. A., LYNN, J. & NEWHAM, D. J. 1989. Changes in force and intracellular metabolites during fatigue of human skeletal muscle. *J Physiol,* 418**,** 311-25.
CALMELS, P. M., NELLEN, M., VAN DER BORNE, I., JOURDIN, P. & MINAIRE, P. 1997. Concentric and eccentric isokinetic assessment of flexor-extensor torque ratios at the hip, knee, and ankle in a sample population of healthy subjects. *Arch Phys Med Rehabil,* 78**,** 1224-30.
CAVANAGH, P. R. & KOMI, P. V. 1979. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *Eur J Appl Physiol Occup Physiol,* 42**,** 159-63.
CHAN, A. Y., LEE, F. L., WONG, P. K., WONG, C. Y. & YEUNG, S. S. 2001. Effects of knee joint angles and fatigue on the neuromuscular control of vastus medialis oblique and vastus lateralis muscle in humans. *Eur J Appl Physiol,* 84**,** 36-41.
CHAN, K. M., MAFFULLI, N., KORKIA, V. & C.T., R. 1996. Principles and Practice of Isokinetics in Sports Medicine and rehabilitation. Williams and Wilkins, Hong Kong,.
CHANG, Y. J., HSU, M. J., CHEN, S. M., LIN, C. H. & WONG, A. M. 2011. Decreased central fatigue in multiple sclerosis patients after 8 weeks of surface functional electrical stimulation. *J Rehabil Res Dev,* 48**,** 555-64.
CHAPPELL, J. D., HERMAN, D. C., KNIGHT, B. S., KIRKENDALL, D. T., GARRETT, W. E. & YU, B. 2005. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med,* 33**,** 1022-9.
CHAUDHURI, A. & BEHAN, P. O. 2000. Neurological dysfunction in chronic fatigue syndrome. *Journal of Chronic Fatigue Syndrome,* 6**,** 51-68.
CLAIBORNE, T. L., TIMMONS, M. K. & PINCIVERO, D. M. 2009. Test-retest reliability of cardinal plane isokinetic hip torque and EMG. *J Electromyogr Kinesiol,* 19**,** e345-52.
CLARKSON, P. M. & KROLL, W. 1978. Practice effects on fractionated response time related to age and activity level. *J Mot Behav,* 10**,** 275-86.
CLARYS, J. P. 1985. Hydrodynamics and electromyography: ergonomics aspects in aquatics. *Appl Ergon,* 16**,** 11-24.
CLARYS, J. P. 2000. Electromyography in sports and occupational settings: an update of its limits and possibilities. *Ergonomics,* 43**,** 1750-62.
CLARYS, J. P. & CABRI, J. 1993. Electromyography and the study of sports movements: a review. *J Sports Sci,* 11**,** 379-448.
COLBY, S., FRANCISCO, A., YU, B., KIRKENDALL, D., FINCH, M. & GARRETT, W. 2000. Electromyographic and kinematic analysis of cutting maneuvers: implications for anterior cruciate ligament injury. / Analyse electromyographique et cinematique de mouvements de deplacement lateral: implications pour les blessures du ligament croise anterieur. *American Journal of Sports Medicine,* 28**,** 234-240.
COLLIANDER, E. B. & TESCH, P. A. 1989. Bilateral eccentric and concentric torque of quadriceps and hamstring muscles in females and males. *European Journal of Applied Physiology & Occupational Physiology,* 59**,** 227-232.
COMETTI, G., MAFFIULETTI, N. A., POUSSON, M., CHATARD, J. C. & MAFFULLI, N. 2001. Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int J Sports Med,* 22**,** 45-51.

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.

COOMBS, R., GARBUTT, G. & CRAMP, M. 2002. Comparison of conventional and functional hamstring-quadriceps moment ratios through a 90 degree range of leg motion. (Abstract) / Comparaison des indices de contraction conventionnelle et fonctionnelle des quadriceps ischio-jambiers a travers une amplitude de 90 degre des mouvements de la jambe.) (Resume. *Journal of Sports Sciences,* 20**,** 3-4.

COPLIN, T. H. 1971. Isokinetic exercise: clinical usage. *National Athletic Trainers Association,* 5**,** 196-200.

CORCOS, D. M., GOTTLIEB, G. L., LATASH, M. L., ALMEIDA, G. L. & AGARWAL, G. C. 1992. Electromechanical delay: An experimental artifact. *Journal of Electromyography and Kinesiology,* 2**,** 59-68.

CORNU, C. & GOUBEL, F. 2001. Musculo-tendinous and joint elastic characteristics during elbow flexion in children. *Clin Biomech (Bristol, Avon),* 16**,** 758-64.

COSTAIN, R. & WILLIAMS, A. K. 1984. lsokinetic Quadriceps and Hamstring Torque Levels of Adolescent, Female Soccer Players. *J Orthop Sports Phys Ther,* 5**,** 196-200.

CRAM, J., KASMAN, G. & HOLTZ, J. 1998. Introduction to Surface Electromyography. Gaithersburg, MD: Aspen Publishing.

CROCE, R. V., PITETTI, K. H., HORVAT, M. & MILLER, J. 1996. Peak torque, average power, and hamstrings/quadriceps ratios in nondisabled adults and adults with mental retardation. *Arch Phys Med Rehabil,* 77**,** 369-72.

CROISIER, J. L., FORTHOMME, B., NAMUROIS, M. H., VANDERTHOMMEN, M. & CRIELAARD, J. M. 2002. Hamstring muscle strain recurrence and strength performance disorders. *Am J Sports Med,* 30**,** 199-203.

CROIX, M. D. S. & KORFF, T. 2011. *Paediatric Biomechanics and Motor Control: Theory and Application,* Taylor & Francis.

DE LOES, M., DAHLSTEDT, L. J. & THOMEE, R. 2000. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scandinavian Journal of Medicine & Science in Sports,* 10**,** 90.

DE LUCA, C. J. 1997. The use of surface electromyography in biomechanics. / Utilisation de l ' electromyographie de surface en biomecanique. *Journal of Applied Biomechanics,* 13**,** 135-163.

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**,** 768-72.

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

DE STE CROIX, M. B. A., FRUER, S., IGA, J., DEIGHAN, M. A. & JAMES, D. 2009b. Non-contact acl and hamstring injuries: eccentric hamstring training for injury prevention. *Exercise, Sports and Health : Second Joint Research Conference in Chemnitz, Germany***,** 124-131.

DECKER, M. J., TORRY, M. R., WYLAND, D. J., STERETT, W. I. & STEADMAN, J. R. 2003. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics,* 18**,** 662-669.

DEDERING, A., ROOS AF HJELMSATER, M., ELFVING, B., HARMS-RINGDAHL, K. & NEMETH, G. 2000. Between-days reliability of subjective and objective assessments of back extensor muscle fatigue in subjects without lower-back pain. *J Electromyogr Kinesiol,* 10**,** 151-8.

DEIGHAN, M. A., CROIX, M. B. A. D. S. & ARMSTRONG, N. 2003. Reliability of isokinetic concentric and eccentric knee and elbow extension and flexion in 9/10 year old boys. *Isokinetics and Exercise Science,* 11**,** 109-115.

DELEXTRAT, A., GREGORY, J. & COHEN, D. 2010. The Use of the Functional H:Q Ratio to Assess Fatigue in Soccer. *International Journal of Sports Medicine,* 31**,** 192-197.

DERMAUX, A. & SANDRA, P. 1999. Applications of capillary electrochromatography. *Electrophoresis,* 20**,** 3027-65.

DEVAN, M. R., PESCATELLO, L. S., FAGHRI, P. & ANDERSON, J. 2004. A Prospective Study of Overuse Knee Injuries Among Female Athletes With Muscle Imbalances and Structural Abnormalities. *J Athl Train,* 39**,** 263-267.

DHAHER, Y. Y., TSOUMANIS, A. D. & RYMER, W. Z. 2003. Reflex muscle contractions can be elicited by valgus positional perturbations of the human knee. *Journal of Biomechanics,* 36**,** 199-209.

DIBREZZO, R., FORT, I. L. & BROWN, B. 1991. Relationships among strength, endurance, weight and body fat during three phases of the menstrual cycle. *J Sports Med Phys Fitness,* 31**,** 89-94.

DICK, R. W. & CAVANAGH, P. R. 1987. 67: A Comparison of Ground Reaction Forces (Grf) During Level and Downhill Running At Similar Speeds. *Medicine & Science in Sports & Exercise,* 19**,** S12.

DRAGANICH, L. F. & VAHEY, J. W. 1990. An in vitro study of anterior cruciate ligament strain induced by quadriceps and hamstrings forces. *J Orthop Res,* 8**,** 57-63.

DROUIN, J. M., VALOVICH-MCLEOD, T. C., SHULTZ, S. J., GANSNEDER, B. M. & PERRIN, D. H. 2004. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *Eur J Appl Physiol,* 91**,** 22-9.

DUCOMPS, C., MAURIEGE, P., DARCHE, B., COMBES, S., LEBAS, F. & DOUTRELOUX, J. P. 2003. Effects of jump training on passive mechanical stress and stiffness in rabbit skeletal muscle: role of collagen. *Acta Physiol Scand,* 178**,** 215-24.

DVIR, Z., EGER, G., HALPERIN, N. & SHKLAR, A. 1989. Thigh muscle activity and anterior cruciate ligament insufficiency. *Clinical Biomechanics,* 4**,** 87-91.

EBSTRUP, J. F. & BOJSEN-MOLLER, F. 2000. Anterior cruciate ligament injury in indoor ball games. / Les blessures du ligament croise anterieur dans les sports collectifs en salle: etude de cas. *Scandinavian Journal of Medicine & Science in Sports,* 10**,** 114-116.

ECCLES, J. C. 1981. Physiology of motor control in man. *Appl Neurophysiol,* 44**,** 5-15.

EDMAN, K. A. & LOU, F. 1992. Myofibrillar fatigue versus failure of activation during repetitive stimulation of frog muscle fibres. *J Physiol,* 457**,** 655-73.

EDWARDS, R. 1981. Human muscle function and fatigue. *Ciba Found Symp,* 82**,** 1–18.

EKSTRAND, J., GILLQUIST, J., MOELLER, M., OEBERG, B. & LILJEDAHL, S. O. 1983. Incidence of soccer injuries and their relation to training and team success. / Incidence des traumatismes en football et leurs relations avec l ' entrainement et la reussite de l ' equipe. *American Journal of Sports Medicine,* 11**,** 63-67.

EKSTRAND, J., HAGGLUND, M. & WALDEN, M. 2011. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med,* 45**,** 553-8.

ELFTMAN, H. 1966. Biomechanics of muscle with particular application to studies of gait. *J Bone Joint Surg Am,* 48**,** 363-77.

ELFVING, B., NEMETH, G., ARVIDSSON, I. & LAMONTAGNE, M. 1999. Reliability of EMG spectral parameters in repeated measurements of back muscle fatigue. *J Electromyogr Kinesiol,* 9**,** 235-43.

ELLENBECKER, T. S. & ROETERT, E. P. 1995. Concentric isokinetic quadricep and hamstring strength in elite junior tennis players. / La force isocinetique concentrique de quadriceps et des muscles de la loge posterieure de la cuisse chez des joueurs juniors d ' elite en tennis. *Isokinetics & Exercise Science,* 5**,** 3-6.

ENGSTRÖM, B., JOHANSSON, C. & TÖRNKVIST, H. 1991. Soccer injuries among elite female players. *Am J Sports Med,* 19**,** 372-375.
ENOKA, R. M. 1996. Eccentric contractions require unique activation strategies by the nervous system. *J Appl Physiol,* 81**,** 2339-46.
ENOKA, R. M. & STUART, D. G. 1992. Neurobiology of muscle fatigue. *J Appl Physiol,* 72**,** 1631-48.
ESPOSITO, F., CE, E., RAMPICHINI, S. & VEICSTEINAS, A. 2009. Acute passive stretching in a previously fatigued muscle: Electrical and mechanical response during tetanic stimulation. *Journal of Sports Sciences,* 27**,** 1347-1357.
ESTON, R., BYRNE, C. & TWIST, C. 2003. Muscle function after exercise-induced muscle damage: considerations for athletic performance in children and adults. *Journal of Exercise Science & Fitness,* 1**,** 85-96.
ESTON, R. & REILLY, T. 2001. Kinanthropometry and exercise physiology laboratory manual: tests, procedures and data. *volume 2: exercise physiology. Second edition*.
ESTON, R. G., FINNEY, S., BAKER, S. & BALTZOPOULOS, V. 1996. Muscle tenderness and peak torque changes after downhill running following a prior bout of isokinetic eccentric exercise. *J Sports Sci,* 14**,** 291-9.
ESTON, R. G., MICKLEBOROUGH, J. & BALTZOPOULOS, V. 1995. Eccentric activation and muscle damage: biomechanical and physiological considerations during downhill running. *Br J Sports Med,* 29**,** 89-94.
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.
FARINA, D. 2006. Interpretation of the surface electromyogram in dynamic contractions. *Exerc Sport Sci Rev,* 34**,** 121-7.
FARINA, D., MERLETTI, R. & ENOKA, R. M. 2004. The extraction of neural strategies from the surface EMG. *J Appl Physiol,* 96**,** 1486-95.
FAUNO, P. & WULFF JAKOBSEN, B. 2006. Mechanism of Anterior Cruciate Ligament Injuries in Soccer. *International Journal of Sports Medicine,* 27**,** 75-79.
FEAGIN, J. A. & LAMBERT, K. L. 1985. Mechanism of injury and pathology of anterior cruciate ligament injuries. *Orthopedic Clinics of North America,* 16**,** 41-45.
FERRETTI, A., PAPANDREA, P., CONTEDUCA, F. & MARIANI, P. P. 1992. Knee ligament injuries in volleyball players. *American Journal of Sports Medicine,* 20**,** 203-207.
FILLYAW, M., BEVINS, T. & FERNANDEZ, L. 1986. Importance of correcting isokinetic peak torque for the effect of gravity when calculating knee flexor to extensor muscle ratios. *Physical Therapy,* 66**,** 23-29.
FINNI, T. & SULIN, C. 2009. Variability in Lateral Positioning of Surface EMG Electrodes. *Journal of Applied Biomechanics,* 25**,** 396-400.
FINUCANE, S. D., RAFEEI, T., KUES, J., LAMB, R. L. & MAYHEW, T. P. 1998. Reproducibility of electromyographic recordings of submaximal concentric and eccentric muscle contractions in humans. *Electroencephalogr Clin Neurophysiol,* 109**,** 290-6.
FLEMING, B. C., OHLEN, G., RENSTROM, P. A., PEURA, G. D., BEYNNON, B. D. & BADGER, G. J. 2003. The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. *Am J Sports Med,* 31**,** 701-7.
FORBES, H., BULLERS, A., LOVELL, A., MCNAUGHTON, L. 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.

FOWLER, N. E. & REILLY, T. 1993. SSESSMENT OF MUSCLE STRENGTH ASYMMETRY IN SOCCER PLAYERS. *Contemporary Ergonomics, (ed. E. J. Lovesey), Toylor and Francis, London, ,* 1**,** 327 - 332.

FRIDEN, C., HIRSCHBERG, A. L. & SAARTOK, T. 2003. Muscle strength and endurance do not significantly vary across 3 phases of the menstrual cycle in moderately active premenopausal women. *Clinical Journal of Sport Medicine,* 13**,** 238-241.

FRIDEN, J., SJOSTROM, M. & EKBLOM, B. 1983. Myofibrillar damage following intense eccentric exercise in man. *Int J Sports Med,* 4**,** 170-6.

FUGLEVAND, A. J. 1995. The role of the sarcolemma action potential in fatigue. *Adv Exp Med Biol,* 384**,** 101-8.

GABRIEL, D. A. & BOUCHER, J. P. 1998. Effects of repetitive dynamic contractions upon electromechanical delay. *Eur J Appl Physiol Occup Physiol,* 79**,** 37-40.

GANDEVIA, S. C. 1998. Neural control in human muscle fatigue: changes in muscle afferents, motoneurones and motor cortical drive [corrected]. *Acta Physiol Scand,* 162**,** 275-83.

GANDEVIA, S. C. 2001. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev,* 81**,** 1725-89.

GARRANDES, F., COLSON, S. S., PENSINI, M. & LEGROS, P. 2007. Time course of mechanical and neuromuscular characteristics of cyclists and triathletes during a fatiguing exercise. *Int J Sports Med,* 28**,** 148-56.

GAUFFIN, H. & TROPP, H. 1992. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med,* 20**,** 182-92.

GAUL, C. A. 1996. Muscular strength and endurance. *In Measurement in pediatric exercise science, Human Kinetics Publishers, p.225-258.* United States.

GEORGOULIS, A. D., RISTANIS, S., PAPADONIKOLAKIS, A., TSEPIS, E., MOEBIUS, U., MORAITI, C. & STERGIOU, N. 2005. Electromechanical delay of the knee extensor muscles is not altered after harvesting the patellar tendon as a graft for ACL reconstruction: implications for sports performance. *Knee Surg Sports Traumatol Arthrosc,* 13**,** 437-43.

GERODIMOS, V., MANDOU, V., ZAFEIRIDIS, A., IOAKIMIDIS, P., STAVROPOULOS, N. & KELLIS, S. 2003. Isokinetic peak torque and hamstring/quadriceps ratios in young basketball players. *Journal of Sports Medicine & Physical Fitness,* 43**,** 444-452.

GHENA, D. R., KURTH, A. L., THOMAS, M. & MAYHEW, J. 1991. Torque Characteristics of the Quadriceps and Hamstring Muscles during Concentric and Eccentric Loading. *J Orthop Sports Phys Ther,* 14**,** 149-54.

GIBALA, M. J., MACDOUGALL, J. D., TARNOPOLSKY, M. A., STAUBER, W. T. & ELORRIAGA, A. 1995. Changes in human skeletal muscle ultrastructure and force production after acute resistance exercise. *J Appl Physiol,* 78**,** 702-8.

GLEESON, M., BLANNIN, A. K., WALSH, N. P., FIELD, C. N. & PRITCHARD, J. C. 1998a. Effect of exercise-induced muscle damage on the blood lactate response to incremental exercise in humans. *Eur J Appl Physiol Occup Physiol,* 77**,** 292-5.

GLEESON, N., MERCER, T. & CAMPBELL, I. 1995. Effects of a fatigue task on absolute and relativized indices of isokinetics leg strengh in female collegiate soccer players *Italian Journal of Sports Traumatology,* 13**,** 502-503.

GLEESON, N. P. 2001. ASSESSMENT OF NEUROMUSCULAR PERFORMANCE USING ELECTROMYOGRAPHY. Kinanthropometry and Exercise Physiology Laboratory Manual: Tests, Procedures and Data. *Volume One: Anthropometry and Volume Two: Exercise Physiology (edited by R. G. Eston and T. Reilly). Routledge: London.*

GLEESON, N. P. & MERCER, T. H. 1996. The utility of isokinetic dynamometry in the assessment of human muscle function. *Sports Med,* 21**,** 18-34.

GLEESON, N. P., REILLY, T., MERCER, T. H., RAKOWSKI, S. & REES, D. 1998b. Influence of acute endurance activity on leg neuromuscular and musculoskeletal performance. *Med Sci Sports Exerc,* 30**,** 596-608.

GLOUCESTERSHIRE, U. O. 2008. Sport and Exercise Laboratories General Procedures; Version 2008.1. *University of Gloucestershire*.

GOOD, L., ODENSTEN, M. & GILLQUIST, J. 1991. Intercondylar notch measurements with special reference to anterior cruciate ligament surgery. *Clin Orthop Relat Res***,** 185-9.

GOSLIN, B. R. & CHARTERIS, J. 1979. Isokinetic dynamometry: normative data for clinical use in lower extremity (knee) cases. *Scandinavian Journal of Rehabilitation Medicine,* 11**,** 105-109.

GOUBEL, F. & MARINI, J. F. 1987. Fibre type transition and stiffness modification of soleus muscle of trained rats. *Pflugers Arch,* 410**,** 321-5.

GRABINER, M. D. 1986. Bioelectric characteristics of the electromechanical delay preceding concentric contraction. *Med Sci Sports Exerc,* 18**,** 37-43.

GRABINER, M. D. & OWINGS, T. M. 1999. Effects of eccentrically and concentrically induced unilateral fatigue on the involved and uninvolved limbs. *J Electromyogr Kinesiol,* 9**,** 185-9.

GRANATA, K. P., IKEDA, A. J. & ABEL, M. F. 2000. Electromechanical delay and reflex response in spastic cerebral palsy. *Arch Phys Med Rehabil,* 81**,** 888-94.

GRAY, J., TAUNTON, J. E., MCKENZIE, D. C., CLEMENT, D. B., MCCONKEY, J. P. & DAVIDSON, R. G. 1985. A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *International Journal of Sports Medicine,* 6**,** 314-316.

GREEN, H. J. 1995. Metabolic determinants of activity induced muscular fatigue. *In, Hargreaves, M. (ed.), Exercise metabolism, Champaign, Ill., Human Kinetics Publishers, c1995, p. 211-256.* United States.

GREEN, H. J. 1997. Mechanisms of muscle fatigue in intense exercise. / Mecanismes de la fatigue musculaire lors de l ' exercice intense. *Journal of Sports Sciences,* 15**,** 247-256.

GRIFFIN, L. Y., AGEL, J., ALBOHM, M. J., ARENDT, E. A., DICK, R. W., GARRETT, W. E., GARRICK, J. G., HEWETT, T. E., HUSTON, L., IRELAND, M. L., JOHNSON, R. J., KIBLER, W. B., LEPHART, S., LEWIS, J. L., LINDENFELD, T. N., MANDELBAUM, B. R., MARCHAK, P., TEITZ, C. C. & WOJTYS, E. M. 2000. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg,* 8**,** 141-50.

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.

GRIMBY, G. & EINARSSON, G. 1987. Muscle morphology with special reference to muscle strength in post-polio subjects. *Birth Defects Orig Artic Ser,* 23**,** 265-74.

GROSSET, J.-F., PISCIONE, J., LAMBERTZ, D. & PÉROT, C. 2011. Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. *European Journal of Applied Physiology***,** 1-9.

GROSSET, J. F., MORA, I., LAMBERTZ, D. & PEROT, C. 2005. Age-related changes in twitch properties of plantar flexor muscles in prepubertal children. *Pediatr Res,* 58**,** 966-70.

GROSSET, J. F., PISCIONE, J., LAMBERTZ, D. & PEROT, C. 2009. Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. *Eur J Appl Physiol,* 105**,** 131-9.

GUR, H. 1997. Concentric and eccentric isokinetic measurements in knee muscles during the menstrual cycle: a special reference to reciprocal moment ratios. *Arch Phys Med Rehabil,* 78**,** 501-5.

GWINN, D. E., WILCKENS, J. H., MCDEVITT, E. R., ROSS, G. & KAO, T. C. 2000. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. / Frequence relative des blessures du ligament croise anterieur chez des hommes et des femmes a l'Academie Navale des Etats-Unis. *American Journal of Sports Medicine,* 28**,** 98-102.

HAGOOD, S., SOLOMONOW, M., BARATTA, R., ZHOU, B. H. & D'AMBROSIA, R. 1990. The effect of joint velocity on the contribution of the antagonist musculature to knee stiffness and laxity. *Am J Sports Med,* 18**,** 182-7.

HAKKINEN, K. & KOMI, P. V. 1983. Changes in neuromuscular performance in voluntary and reflex contraction during strength training in man. *Int J Sports Med,* 4**,** 282-8.

HÄKKINEN, K. & KOMI, P. V. 1983b. Electromyographic and mechanical characteristics of human skeletal muscle during fatigue under voluntary and reflex conditions. *Electroencephalography and Clinical Neurophysiology,* 55**,** 436-444.

HALIN, R., GERMAIN, P., BERCIER, S., KAPITANIAK, B. & BUTTELLI, O. 2003. Neuromuscular response of young boys versus men during sustained maximal contraction. *Med Sci Sports Exerc,* 35**,** 1042-8.

HAMILL, C. L., CLARKE, I. E., FREDERICK, E. G., GOODYEAR, L. J. & HOWLEY, E. T. 1984. Effects of Grade Running on Kinematics and Impact Force. *Medicine & Science in Sports & Exercise,* 16**,** 184.

HAWKINS, R. D. & FULLER, C. W. 1996. Risk assessment in professional football: an examination of accidents and incidents in the 1994 World Cup finals. / Evaluation du risque en football professionnel: etude des accidents et incidents lors des phases finales de la coupe du monde 1994. *British Journal of Sports Medicine,* 30**,** 165-170.

HAWKINS, R. D. & FULLER, C. W. 1998. An examination of the frequency and severity of injuries and incidents at three levels of professional football. / Etude de la frequence et de la severite des blessures et incidents de jeu en football professionnel, a trois niveaux differents. *British Journal of Sports Medicine,* 32**,** 326-331.

HAWKINS, R. D. & FULLER, C. W. 1999. A prospective epidemiological study of injuries in four English professional football clubs. / Etude epidemiologique prospective des blessures survenues chez les joueurs de quatre clubs de football professionnels anglais. *British Journal of Sports Medicine,* 33**,** 196-203.

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. *Br J Sports Med,* 35**,** 43-7.

HEIDERSCHEIT, B. C., HAMILL, J. & CALDWELL, G. E. 2000. Influence of Q-angle on lower-extremity running kinematics. *Journal of Orthopaedic & Sports Physical Therapy,* 30**,** 271-278.

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., JENNIFER, H., DORFMAN, REBECCA, A. & BRAHAM 2004. Lower extremity malalignments and anterior cruciate ligament injury history. *J Sports Sci Med,* 3**,** 220-225.

HEWETT, T., SHULTZ, S. & GRIFFIN, L. 2007. Understanding and Preventing Noncontact ACL Injuries *In:* MEDICINE, A. O. S. F. S. (ed.).

HEWETT, T. E., LINDENFELD, T. N., RICCOBENE, J. V. & NOYES, F. R. 1999. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. / Effet d'un entrainement neuromusculaire sur l'incidence de blessures au genou chez des athletes feminines. *American Journal of Sports Medicine,* 27**,** 699-706.

HEWETT, T. E., MYER, G. D. & FORD, K. R. 2001. Prevention of anterior cruciate ligament injuries. *Current Women's Health Reports,* 1**,** 218-224.

HEWETT, T. E., MYER, G. D. & FORD, K. R. 2004. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am,* 86-A**,** 1601-8.

HEWETT, T. E., MYER, G. D. & FORD, K. R. 2006. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med,* 34**,** 299-311.

HEWETT, T. E., MYER, G. D., FORD, K. R., HEIDT JR, R. S., COLOSIMO, A. J., MCLEAN, S. G., VAN DEN BOGERT, A. J., PATERNO, M. V. & SUCCOP, P. 2005. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes A Prospective Study. *American Journal of Sports Medicine,* 33**,** 492-501.

HEWETT, T. E., MYER, G. D. & ZAZULAK, B. T. 2008. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. *J Sci Med Sport,* 11**,** 452-9.

HEWETT, T. E., PATERNO, M. V. & MYER, G. D. 2002. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res***,** 76-94.

HEWETT, T. E., STROUPE, A. L., NANCE, T. A. & NOYES, F. R. 1996. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med,* 24**,** 765-73.

HICKNER, R. C., MEHTA, P. M., DYCK, D., DEVITA, P., HOUMARD, J. A., KOVES, T. & BYRD, P. 2001. Relationship between fat-to-fat-free mass ratio and decrements in leg strength after downhill running. *J Appl Physiol,* 90**,** 1334-41.

HIEMSTRA, L. A., LO, I. K. & FOWLER, P. J. 2001. Effect of fatigue on knee proprioception: implications for dynamic stabilization. *J Orthop Sports Phys Ther,* 31**,** 598-605.

HILL, A. V. 1938. The Heat of Shortening and the Dynamic Constants of Muscle. *Proceedings of the Royal Society of London. Series B, Biological Sciences,* 126**,** 136-195.

HISLOP, H. J. & MONTGOMERY, J. 2002. *Daniels and Worthingham's muscle testing: techniques of manual examination. 7th ed,* Philadelphia; United States, W.B. Saunders.

HOFF, G. L. & MARTIN, T. A. 1986. Outdoor and indoor soccer: injuries among youth players. / Football d' exterieur et d' interieur: traumatismes chez des jeunes joueurs. *American Journal of Sports Medicine,* 14**,** 231-233.

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 (Allen Press Publishing Services Inc.),* 21**,** 41-47.

HOLE, C. D., SMIT, G. H., HAMMOND, J., KUMAR, A., SAXTON, J. & COCHRANE, T. 2000. Dynamic control and conventional strength ratios of the quadriceps and hamstrings in subjects with anterior cruciate ligament deficiency. *Ergonomics,* 43**,** 1603-9.

HOLMBACK, A. M., PORTER, M. M., DOWNHAM, D., ANDERSEN, J. L. & LEXELL, J. 2003. Structure and function of the ankle dorsiflexor muscles in young and moderately active men and women. *J Appl Physiol,* 95**,** 2416-24.

HOPKINS, J. T., FELAND, J. B. & HUNTER, I. 2007. A comparison of voluntary and involuntary measures of electromechanical delay. *Int J Neurosci,* 117**,** 597-604.

HORITA, T. & ISHIKO, T. 1987. Relationships between muscle lactate accumulation and surface EMG activities during isokinetic contractions in man (Les relations entre l' accumulation du lactate musculaire et l' activite EMG de surface lors de contractions isocinetiques chez l' homme. *European Journal of Applied Physiology,* 56**,** 18-23.

HORSTMANN, T., MAYER, F., MASCHMANN, J., NIESS, A., ROECKER, K. & DICKHUTH, H. H. 2001. Metabolic reaction after concentric and eccentric endurance-exercise of the knee and ankle. *Med Sci Sports Exerc,* 33**,** 791-5.

HORTON, M. G. & HALL, T. L. 1989. Quadriceps femoris muscle angle: Normal values and relationships with gender and selected skeletal measures *Physical Therapy,* 69**,** 897-901.

HOUSTON, M. E., NORMAN, R. W. & FROESE, E. A. 1988. Mechanical measures during maximal velocity knee extension exercise and their relation to fibre composition of the human vastus lateralis muscle. *European Journal of Applied Physiology,* 58**,** 1-7.

HOWATSON, G. 2010. The impact of damaging exercise on electromechanical delay in biceps brachii. *Journal of Electromyography & Kinesiology,* 20**,** 477-481.

HOWATSON, G., GLAISTER, M., BROUNER, J. & VAN SOMEREN, K. A. 2009. The reliability of electromechanical delay and torque during isometric and concentric isokinetic contractions. *Journal of Electromyography & Kinesiology,* 19**,** 975-979.

HUGHES, G. & WATKINS, J. 2006. A Risk-Factor Model for Anterior Cruciate Ligament Injury. *Sports Medicine,* 36**,** 411-428.

HUNGERFORD, D. S. & BARRY, M. 1979. Biomechanics of the patellofemoral joint. *Clinical Orthopaedics and Related Research,* 144**,** 9-15.

HUNTER R., L. M. 1988. sports injury research. *American Journal of Sports Medicine,* 16**,** s25-s37.

HUSTON, L. J. & WOJTYS, E. M. 1996. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med,* 24**,** 427-36.

HUTCHINSON, M. R. & IRELAND, M. I. 1995. Knee injuries in female athletes. *Sports Medicine,* 19**,** 288-302.

IACONO, C. U. 2004. Test-retest reliability of static EMG scan configural profiling. *Appl Psychophysiol Biofeedback,* 29**,** 35-50.

IGA, J., GEORGE, K., LEES, A. & REILLY, T. 2006. Reliability of Assessing Indices of Isokinetic Leg Strength in Pubertal Soccer Players. Pediatric Exercise Science, 18, 436-445.

INKLAAR, H. 1994. Soccer injuries: I: incidence and severity. *Sports Medicine,* 18**,** 55-73.

IVERSEN, J. R. & MCMAHON, T. A. 1992. Running on an incline. *J Biomech Eng,* 114**,** 435-41.

JAMES, C. R., SIZER, P. S., STARCH, D. W., LOCKHART, T. E. & SLAUTERBECK, J. 2004. Gender differences among sagittal plane knee kinematic and ground reaction force characteristics during a rapid sprint and cut maneuver. *Research Quarterly for Exercise & Sport,* 75**,** 31-38.

JANSE DE JONGE, X. A., BOOT, C. R., THOM, J. M., RUELL, P. A. & THOMPSON, M. W. 2001. The influence of menstrual cycle phase on skeletal muscle contractile characteristics in humans. *J Physiol,* 530**,** 161-6.

JAWOROWSKI, A., PORTER, M. M., HOLMBACK, A. M., DOWNHAM, D. & LEXELL, J. 2002. Enzyme activities in the tibialis anterior muscle of young moderately active men and women: relationship with body composition, muscle cross-sectional area and fibre type composition. *Acta Physiol Scand,* 176**,** 215-25.

JOHANSSON, H., SJOLANDER, P. & SOJKA, P. 1991a. A sensory role for the cruciate ligaments. *Clin Orthop Relat Res***,** 161-78.

JOHANSSON, H., SJOLANDER, P. & SOJKA, P. 1991b. Receptors in the knee joint ligaments and their role in the biomechanics of the joint. *Crit Rev Biomed Eng,* 18**,** 341-68.

JOHNSON, J. & SIEGEL, D. 1978. Reliability of an isokinetic movement of the knee extensors. *Res Q,* 49**,** 88-90.

JONES, C., ALLEN, T., TALBOT, J., MORGAN, D. L. & PROSKE, U. 1997. Changes in the mechanical properties of human and amphibian muscle after eccentric exercise. *Eur J Appl Physiol Occup Physiol,* 76**,** 21-31.

JONES, D., ROUND, J. & HAAN, A. D. 2004. *Skeletal muscles from molecules movement: A texbook of muscle physiology, phsiotherapy and medicine,* London: Churchill Livingstone.

JONSSON, B. 1978. Kinesiology: with special reference to electromyographic kinesiology. *Electroencephalogr Clin Neurophysiol Suppl***,** 417-28.

KALUND, S., SINKJAER, T., ARENDT-NIELSEN, L. & SIMONSEN, O. 1990. Altered timing of hamstring muscle action in anterior cruciate ligament deficient patients. *Am J Sports Med,* 18**,** 245-8.

KAMEN, G., KROLL, W., CLARKSON, P. M. & ZIGON, S. T. 1981. Fractioned reaction time in power-trained and endurance-trained athletes under conditions of fatiguing isometric exercise. *J Mot Behav,* 13**,** 117-29.

KAMINSKI, T. W. & DOVER, G. C. 2001. Reliability of inversion and eversion peak- and average-torque measurements from the Biodex System 3 dynamometer. / Efficacite des mesures d ' inversion et d ' eversion du moment de torsion maximal et moyen a partir d ' un dynamometre appele Biodex System 3. *Journal of Sport Rehabilitation,* 10**,** 205-220.

KAMINSKI, T. W., PERRIN, D. H., MATTACOLA, C. G., SZCZERBA, J. E. & BERNIER, J. N. 1995. The reliability and validity of ankle inversion and eversion torque measurements from the Kin Com II isokinetic dynamometer. *Journal of Sport Rehabilitation,* 4**,** 210-218.

KANEHISA, H., OKUYAMA, H., IKEGAWA, S. & FUKUNAGA, T. 1996. Sex difference in force generation capacity during maximal knee extensions. / Difference de sexe sur la capacite de generation de la force lors d ' extensions du genou repetees. *European Journal of Applied Physiology & Occupational Physiology,* 73**,** 557-562.

KANKAANPAA, M., TAIMELA, S., LAAKSONEN, D., HANNINEN, O. & AIRAKSINEN, O. 1998. Back and hip extensor fatigability in chronic low back pain patients and controls. *Arch Phys Med Rehabil,* 79**,** 412-7.

KANNUS, P. 1988. Ratio of hamstring to quadriceps femoris muscles' strength in the anterior cruciate ligament insufficient knee. Relationship to long-term recovery. *Phys Ther,* 68**,** 961-5.

KANNUS, P. 1994. Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. *Int J Sports Med,* 15 Suppl 1**,** S11-8.

KATZ, B. 1939. The relation between force and speed in muscular contraction. *J Physiol,* 96**,** 45-64.

KAWAKAMI, Y., KANEHISA, H., IKEGAWA, S. & FUKUNAGA, T. 1993. Concentric and eccentric muscle strength before, during and after fatigue in 13 year-old boys. *Eur J Appl Physiol Occup Physiol,* 67**,** 121-4.

KEENE, G. C. R., BICKERSTAFF, D., RAE, P. J. & PATERSON, R. S. 1993. The natural history of meniscal tears in anterior cruciate ligament insufficiency. *American Journal of Sports Medicine,* 21**,** 672-679.

KELLIS, E. 1996. Reliability of isokinetic eccentric and concentric moments of knee extensors and flexors using the Biodex dynamometer. *Proceeding of the British Association of Sport and Exercise Annual Conference, (Abstract*.

KELLIS, E. 1998. Quantification of quadriceps and hamstring antagonist activity. *Sports Med,* 25**,** 37-62.

KELLIS, E. & BALTZOPOULOS, V. 1995. Isokinetic eccentric exercise. *Sports Med,* 19**,** 202-22.

KELLIS, E. & BALTZOPOULOS, V. 1998. Muscle activation differences between eccentric and concentric isokinetic exercise. *Med Sci Sports Exerc*, 30**,** 1616-23.

KELLIS, E. & KATIS, A. 2007. Quantification of functional knee flexor to extensor moment ratio using isokinetics and electromyography. *Journal of Athletic Training,* 42**,** 477-85.

KELLIS, E. & KATIS, A. 2008. Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions. *J Electromyogr Kinesiol,* 18**,** 351-8.

KENT-BRAUN, J. A. 1999. Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort. *Eur J Appl Physiol Occup Physiol,* 80**,** 57-63.

KENT-BRAUN, J. A., NG, A. V., DOYLE, J. W. & TOWSE, T. F. 2002. Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. *J Appl Physiol,* 93**,** 1813-23.

KERNOZEK, T. W., TORRY, M. R. & IWASAKI, M. 2008. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med,* 36**,** 554-65.

KNAPIK, J. J., BAUMAN, C. L., JONES, B. H., HARRIS, J. M. & VAUGHAN, L. 1991. Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. / Les desequilibres entre la force et la souplesse associees aux blessures dues a la pratique du sport chez des femmes athletes universitaires, avant la saison. *American Journal of Sports Medicine,* 19**,** 76-81.

KNUTSON, L. M., SODERBERG, G. L., BALLANTYNE, B. T. & CLARKE, W. R. 1994. A study of various normalization procedures for within day electromyographic data. *J Electromyogr Kinesiol,* 4**,** 47-59.

KOLLMITZER, J., EBENBICHLER, G. R. & KOPF, A. 1999. Reliability of surface electromyographic measurements. *Clin Neurophysiol,* 110**,** 725-34.

KOMI, P. V. & BOSCO, C. 1978. Utilization of stored elastic energy in leg extensor muscles by men and women. *Med Sci Sports,* 10**,** 261-5.

KOMI, P. V., LINNAMO, V., SILVENTOINEN, P. & SILLANPAA, M. 2000. Force and EMG power spectrum during eccentric and concentric actions. *Med Sci Sports Exerc,* 32**,** 1757-62.

KONG, P. W. & BURNS, S. F. 2010. Bilateral difference in hamstrings to quadriceps ratio in healthy males and females. *Phys Ther Sport,* 11**,** 12-7.

KOVANEN, V., SUOMINEN, H. & HEIKKINEN, E. 1980. Connective tissue of "fast" and "slow" skeletal muscle in rats--effects of endurance training. *Acta Physiol Scand,* 108**,** 173-80.

KRNJEVIC, K. & MILEDI, R. 1959. Presynaptic failure of neuromuscular propagation in rats. *J Physiol,* 149**,** 1-22.

KROLL, W. 1974. Fractionated reaction and reflex time before and after fatiguing isotonic exercise. *Med Sci Sports,* 6**,** 260-6.

KROSSHAUG, T., ANDERSEN, T. E., OLSEN, O. E. O., MYKLEBUST, G. & BAHR, R. 2005a. Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. *British Journal of Sports Medicine,* 39**,** 330-339.

KROSSHAUG, T. & BAHR, R. 2005b. A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. *Journal of Biomechanics,* 38**,** 919-929.

KROSSHAUG, T., NAKAMAE, A., BODEN, B., ENGEBRETSEN, L., SMITH, G., SLAUTERBECK, J., HEWETT, T. E. & BAHR, R. 2007a. Estimating 3D joint kinematics from video sequences of running and cutting maneuvers—assessing the accuracy of simple visual inspection. *Gait & Posture,* 26**,** 378-385.

KROSSHAUG, T., NAKAMAE, A., BODEN, B. P., ENGEBRETSEN, L., SMITH, G., SLAUTERBACK, J. R., HEWETT, T. E. & BAHR, R. 2007b. Mechanisms of Anterior

Cruciate Ligament Injury in Basketball Video Analysis of 39 Cases. *American Journal of Sports Medicine,* 35**,** 359-367.

KROSSHAUG, T., SLAUTERBECK, J. R., ENGEBRETSEN, L. & BAHR, R. 2007c. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scandinavian Journal of Medicine & Science in Sports,* 17**,** 508-519.

KUBO, K., AKIMA, H., KOUZAKI, M., ITO, M., KAWAKAMI, Y., KANEHISA, H. & FUKUNAGA, T. 2000. Changes in the elastic properties of tendon structures following 20 days bed-rest in humans. *Eur J Appl Physiol,* 83**,** 463-8.

KUBO, K., KANEHISA, H., ITO, M. & FUKUNAGA, T. 2001. Effects of isometric training on the elasticity of human tendon structures in vivo. *J Appl Physiol,* 91**,** 26-32.

LACOURPAILLE, L., NORDEZ, A. & HUG, F. 2012. Influence of stimulus intensity on electromechanical delay and its mechanisms. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*.

LALODA, F., ROSS, A. & ISSEL, W. 1974. EMG Primer: A Guide to Practical Electromyography and Electroneurography. New York, NY: Springer- Verlag.

LAMBERT, C. P., ARCHER, R. L. & EVANS, W. J. 2001. Muscle strength and fatigue during isokinetic exercise in individuals with multiple sclerosis. / Force et fatigue musculaire pendant un exercice isocinetique chez des personnes atteintes de sclerose en plaques. *Medicine & Science in Sports & Exercise,* 33**,** 1613-1619.

LAMBERTZ, D., MORA, I., GROSSET, J. F. & PEROT, C. 2003. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J Appl Physiol,* 95**,** 64-72.

LAMBSON, R. B., BARNHILL, B. S. & HIGGINS, R. W. 1996. Football cleat design and its effect on anterior cruciate ligament injuries: a three-year prospective study. *American Journal of Sports Medicine,* 24**,** 155-159.

LANZA, I. R., BEFROY, D. E. & KENT-BRAUN, J. A. 2005. Age-related changes in ATP-producing pathways in human skeletal muscle in vivo. *J Appl Physiol,* 99**,** 1736-44.

LAPRADE, R. F. & BURNETT, Q. M. 1994. Femoral intercodylar notch stenosis and correlation to anterior cruciate ligament injuries. A prospective study. *American Journal of Sports Medicine,* 22**,** 198-203.

LARSSON, B., KARLSSON, S., ERIKSSON, M. & GERDLE, B. 2003. Test-retest reliability of EMG and peak torque during repetitive maximum concentric knee extensions. *J Electromyogr Kinesiol,* 13**,** 281-7.

LATASH, M. L. 1998. *Neurophysiological basis of movement,* Champaign, IL, Human Kinetics.

LATTANZIO, P. J., PETRELLA, R. J., SPROULE, J. R. & FOWLER, P. J. 1997. Effects of fatigue on knee proprioception. *Clin J Sport Med,* 7**,** 22-7.

LEBRUN, C. M., MCKENZIE, D. C., PRIOR, J. C. & TAUNTON, J. E. 1995. Effects of menstrual cycle phase on athletic performance. *Medicine & Science in Sports & Exercise,* 27**,** 437-444.

LEPHART, S., RIEMANN, M. & FU, F. 2000. Introduction to the sensorimotor system, in Proprioception and neuromuscular control in joint stability. *S.M. Lephart and F.H. Fu, Editors. 2000, Human Kinetics: Champaign, IL.*

LEWIS, T. 2000. Anterior Cruciate Ligament Injury in Female Athletes: Why are women so vulnerable?: Literature review. *Physiotherapy,* 86**,** 464-472.

LI, L. & BAUM, B. S. 2004. Electromechanical delay estimated by using electromyography during cycling at different pedaling frequencies. *J Electromyogr Kinesiol,* 14**,** 647-52.

LIPPINCOTT, W. A. W. 2010. American College of Sports Medicine ACSM’s Guidelines to Exercise Testing and Prescription. 8th Edition.

LIU, S. H., AL-SHAIKH, R., PANOSSIAN, V., YANG, R. S., NELSON, S. D., SOLEIMAN, N., FINERMAN, G. A. & LANE, J. M. 1996. Primary immunolocalization of estrogen and progesterone target cells in the human anterior cruciate ligament. *J Orthop Res,* 14**,** 526-33.

LLOYD, D. G. 2001. Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. *J Orthop Sports Phys Ther,* 31**,** 645-54; discussion 661.

LLOYD, D. G., BUCHANAN, T. S. & BESIER, T. F. 2005. Neuromuscular biomechanical modeling to understand knee ligament loading. *Med Sci Sports Exerc,* 37**,** 1939-47.

LOFVENBERG, R., KARRHOLM, J., SUNDELIN, G. & AHLGREN, O. 1995. Prolonged reaction time in patients with chronic lateral instability of the ankle. *Am J Sports Med,* 23**,** 414-7.

LOUDON, J. K., JENKINS, W. & LOUDON, K. L. 1996. The relationship between static posture and ACL injury in female athletes. *Journal of Orthopaedic & Sports Physical Therapy,* 24**,** 91-97.

LUND-HANSSEN, H., GANNON, J., ENGEBRETSEN, L., HOLEN, K. & HAMMER, S. 1996. Isokinetic muscle performance in healthy female handball players and players with a unilateral anterior cruciate ligament reconstruction. *Scand J Med Sci Sports,* 6**,** 172-5.

LYSENS, R., VAN DEN AUWEELE, Y., CLAESSENS, A., STEVERLYNCK, A., LEFEVRE, J., RENSON, L. & OSTYN, M. 1984. The predictability of sports injuries. *Sports Medicine,* 1**,** 6-10.

MACINSTOSH, B., GARDINER, P. & MCCOMAS, A. 2005. Skeletalmuscle: formand function. 2nd edition. Human Kinetics Publishers; Champaign, IL, USA,.

MACINTYRE, D. L., SLAWNYCH, M. P., REID, W. D. & MCKENZIE, D. C. 1998. Fatigue of the knee extensor muscles following eccentric exercise. *Electromyogr Clin Neurophysiol,* 38**,** 3-9.

MACLAREN, D. P., GIBSON, H., PARRY-BILLINGS, M. & EDWARDS, R. H. 1989. A review of metabolic and physiological factors in fatigue. *Exerc Sport Sci Rev,* 17**,** 29-66.

MADSEN, O. R. 1996. Trunk extensor and flexor strength measured by the Cybex 6000 dynamometer. Assessment of short-term and long-term reproducibility of several strength variables. *Spine (Phila Pa 1976),* 21**,** 2770-6.

MALISOUX, L., FRANCAUX, M., NIELENS, H. & THEISEN, D. 2006. Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *J Appl Physiol,* 100**,** 771-9.

MALONE, T., HARDAKER, W. & WE, E. A. G. 1993. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Onhop Assoc,* 2**,** 36-39.

MALUF, K. S. & ENOKA, R. M. 2005. Task failure during fatiguing contractions performed by humans. *J Appl Physiol,* 99**,** 389-96.

MANDELBAUM, B. R., SILVERS, H. J., WATANABE, D. S., KNARR, J. F., THOMAS, S. D., GRIFFIN, L. Y., KIRKENDALL, D. T. & GARRETT JR, W. 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.

MANNION, A. F. & DOLAN, P. 1996. Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. *Eur J Appl Physiol Occup Physiol,* 74**,** 411-9.

MARKOLF, K. L., BURCHFIELD, D. M., SHAPIRO, M. M., SHEPARD, M. F., FINERMAN, G. A. & SLAUTERBECK, J. L. 1995. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res,* 13**,** 930-5.

MARKOLF, K. L., GRAFF-RADFORD, A. & AMSTUTZ, H. C. 1978. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am,* 60**,** 664-74.

MARSDEN, C. D., MEADOWS, J. C. & MERTON, P. A. 1983. "Muscular wisdom" that minimizes fatigue during prolonged effort in man: peak rates of motoneuron discharge and slowing of discharge during fatigue. *Adv Neurol,* 39**,** 169-211.

MARSH, A. P. & MARTIN, P. E. 1995. The relationship between cadence and lower extremity EMG in cyclists and noncyclists. *Med Sci Sports Exerc,* 27**,** 217-25.

MATHUR, S., ENG, J. J. & MACINTYRE, D. L. 2005. Reliability of surface EMG during sustained contractions of the quadriceps. *J Electromyogr Kinesiol,* 15**,** 102-10.

MAZZOCCA, A. D., NISSEN, C. W., GEARY, M. & ADAMS, D. J. 2003. Valgus medial collateral ligament rupture causes concomitant loading and damage of the anterior cruciate ligament. *J Knee Surg,* 16**,** 148-51.

MCCOMAS 1996. Skeletal muscle: form and function *Champaign, IL, USA: Human Kinetics*.

MCHUGH, M. P., CONNOLLY, D. A., ESTON, R. G., KREMENIC, I. J., NICHOLAS, S. J. & GLEIM, G. W. 1999. The role of passive muscle stiffness in symptoms of exercise-induced muscle damage. *Am J Sports Med,* 27**,** 594-9.

MCKINNEY, B., CHERNEY, S. & PENNA, J. 2008. Intra-articular knee injuries in patients with knee extensor mechanism ruptures. *Knee Surgery, Sports Traumatology, Arthroscopy,* 16**,** 633-638.

MCLEAN, S. G., FELIN, R. E., SUEDEKUM, N., CALABRESE, G., PASSERALLO, A. & JOY, S. 2007. Impact of Fatigue on Gender-Based High-Risk Landing Strategies. *Medicine & Science in Sports & Exercise,* 39**,** 502-514.

MCLEAN, S. G., NEAL, R. J., MYERS, P. T. & WALTERS, M. R. 1999. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. / Cinematique de l'articulation du genou pendant la manoeuvre dite de l'esquive du pied: potentiel de blessure chez la femme. *Medicine & Science in Sports & Exercise,* 31**,** 959-968.

MCLEOD, T. C. V., ARMSTRONG, T., MILLER, M. & SAUERS, J. L. 2009. Balance Improvements in Female High School Basketball Players After a 6-Week Neuromuscular-Training Program. *Journal of Sport Rehabilitation,* 18**,** 465-481.

MCNAIR, P. J. & MARSHALL, R. N. 1994. Landing characteristics in subjects with normal and anterior cruciate ligament deficient knee joints. *Arch Phys Med Rehabil,* 75**,** 584-9.

MCNAIR, P. J., MARSHALL, R. N. & MATHESON, J. A. 1990. Important features associated with acute anterior cruciate ligament injury. *N Z Med J,* 103**,** 537-9.

MCNEIL, C. J., MARTIN, P. G., GANDEVIA, S. C. & TAYLOR, J. L. 2009. The response to paired motor cortical stimuli is abolished at a spinal level during human muscle fatigue. *J Physiol,* 587**,** 5601-12.

MEEUWISSE, W. H. 1994. Assessing causation in sport injury: a multifactorial model. *Clinical Journal of Sport Medicine,* 4**,** 166-170.

MELNYK, M. & GOLLHOFER, A. 2007. Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. *Knee Surg Sports Traumatol Arthrosc,* 15**,** 525-32.

MERCER, T. H., GLEESON, N. P., CLARIDGE, S. & CLEMENT, S. 1998. Prolonged intermittent high intensity exercise impairs neuromuscular performance of the knee flexors. *Eur J Appl Physiol Occup Physiol,* 77**,** 560-2.

MEYERS, M. C. & BARNHILL, B. S. 2004. Incidence, causes, and severity of high school football injuries on FieldTurf versus natural grass: a 5-year prospective study. *Am J Sports Med,* 32**,** 1626-38.

MILBURN, P. D. & BARRY, E. B. 1998. Shoe-surface interaction and the reduction of injury in rugby union. / Interaction chaussure-surface et reduction des blessures en rugby a quinze. *Sports Medicine,* 25**,** 319-327.

MILLET, G. Y. & LEPERS, R. 2004. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med,* 34**,** 105-16.
MINSHULL, C., GLEESON, N., WALTERS-EDWARDS, M., ESTON, R. & REES, D. 2007. Effects of acute fatigue on the volitional and magnetically-evoked electromechanical delay of the knee flexors in males and females. *Eur J Appl Physiol,* 100**,** 469-78.
MINSHULL, C. Ph.D. awarded 2004. Thesis Title: Exercise, neuromuscular performance and stability of synovial joints, University of Wales, Bangor.

MIZUNO, Y., KUMAGAI, M., MATTESSICH, S. M., ELIAS, J. J., RAMRATTAN, N., COSGAREA, A. J. & CHAO, E. Y. S. 2001. Q-angle influences tibiofemoral and patellofemoral kinematics. *Journal of Orthopaedic Research,* 19**,** 834-840.
MOELLER, J. L. & LAMB, M. M. 1997. Anterior cruciate ligament injuries in female athletes. Why are women more susceptible? / Blessures du ligament croise anterieur chez l ' athlete feminine: les femmes y sont-elles plus sujettes ? *Physician & Sportsmedicine,* 25**,** 31-32;41-42;44;46-48;54.
MOHR, M., KRUSTRUP, P. & BANGSBO, J. 2003. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci,* 21**,** 519-28.
MOORE, B. D., DROUIN, J., GANSNEDER, B. M. & SHULTZ, S. J. 2002. The differential effects of fatigue on reflex response timing and amplitude in males and females. *J Electromyogr Kinesiol,* 12**,** 351-60.
MORA, I., QUINTEIRO-BLONDIN, S. & PEROT, C. 2003. Electromechanical assessment of ankle stability. *Eur J Appl Physiol,* 88**,** 558-64.
MORE, R. C., KARRAS, B. T., NEIMAN, R., FRITSCHY, D., WOO, S. & DANIEL, D. M. 1993. Hamstrings--an anterior cruciate ligament protagonist. An in vitro study. *American Journal of Sports Medicine,* 21**,** 231-237.
MOUL, J. L. 1998. Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA Division I collegiate basketball players. *Journal of Athletic Training,* 33**,** 118-121.
MOUNTCASTLE, S. B., POSNER, M., KRAGH JR, J. F. & TAYLOR, D. C. 2007. Gender Differences in Anterior Cruciate Ligament Injury Vary With Activity Epidemiology of Anterior Cruciate Ligament Injuries in a Young, Athletic Population. *American Journal of Sports Medicine,* 35**,** 1635-1643.
MURAOKA, T., MURAMATSU, T., FUKUNAGA, T. & KANEHISA, H. 2004. Influence of tendon slack on electromechanical delay in the human medial gastrocnemius in vivo. *J Appl Physiol,* 96**,** 540-4.
MURPHY, D. F., CONNOLLY, D. A. J. & BEYNNON, B. D. 2003. Risk factors for lower extremity injury: a review of the literature. / Facteurs de risques pour les traumatismes des membres inferieurs: revue de la litterature. *British Journal of Sports Medicine,* 37**,** 13-29.
MYER, G. D., CHU, D. A., BRENT, J. L. & HEWETT, T. E. 2008. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med,* 27**,** 425-48, ix.
MYER, G. D., FORD, K. R. & HEWETT, T. E. 2004. Rationale and Clinical Techniques for Anterior Cruciate Ligament Injury Prevention Among Female Athletes. *J Athl Train,* 39**,** 352-364.
MYER, G. D., FORD, K. R. & HEWETT, T. E. 2005a. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology,* 15**,** 181-189.
MYER, G. D., FORD, K. R., KHOURY, J., SUCCOP, P. & HEWETT, T. E. 2010. Clinical correlates to laboratory measures for use in non-contact anterior cruciate ligament injury risk prediction algorithm. *Clinical biomechanics (Bristol, Avon),* 25**,** 693-699.

MYER, G. D., FORD, K. R., PALUMBO, J. P. & HEWETT, T. E. 2005b. Neuromuscular Training Improves Performance and Lower-Extremity Biomechanics in Female Athletes. *Journal of Strength & Conditioning Research,* 19**,** 51-60.

MYERS, C. A. & HAWKINS, D. 2010. Alterations to movement mechanics can greatly reduce anterior cruciate ligament loading without reducing performance. *Journal of Biomechanics,* 43**,** 2657-2664.

MYERS, J. B., RIEMANN, B. L., JU, Y. Y., HWANG, J. H., MCMAHON, P. J. & LEPHART, S. M. 2003. Shoulder muscle reflex latencies under various levels of muscle contraction. *Clin Orthop Relat Res***,** 92-101.

MYKLEBUST, G., MAEHLUM, S., ENGEBRETSEN, L., STRAND, T. & SOLHEIM, E. 1997. Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scand J Med Sci Sports,* 7**,** 289-92.

MYKLEBUST, G., MAEHLUM, S., HOLM, I. & BAHR, R. 1998. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. / Etude prospective par cohortes des lesions du ligament croise anterieur chez des joueurs et joueuses de handball norvegiens de haut niveau. *Scandinavian Journal of Medicine & Science in Sports,* 8**,** 149-153.

NAJIBI, S. & ALBRIGHT, J. P. 2005. The Use of Knee Braces, Part 1 Prophylactic Knee Braces in Contact Sports. *American Journal of Sports Medicine,* 33**,** 602-611.

NARICI, M. V., HOPPELER, H., KAYSER, B., LANDONI, L., CLAASSEN, H., GAVARDI, C., CONTI, M. & CERRETELLI, P. 1996. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand,* 157**,** 175-86.

NATIONAL-COLLEGIATE-ATHLETICS-ASSOCIATION 2004. Sport sponsorship and participation report. 1982-2003. Indianapolis, IN: Author.

NEWHAM, D. J., JONES, D. A. & CLARKSON, P. M. 1987. Repeated high-force eccentric exercise: effects on muscle pain and damage. *J Appl Physiol,* 63**,** 1381-6.

NEWHAM, D. J., JONES, D. A., GHOSH, G. & AURORA, P. 1988. Muscle fatigue and pain after eccentric contractions at long and short length. *Clinical Science (London, England: 1979),* 74**,** 553-557.

NEWHAM, D. J., JONES, D. A., TOLFREE, S. E. & EDWARDS, R. H. 1986. Skeletal muscle damage: a study of isotope uptake, enzyme efflux and pain after stepping. *Eur J Appl Physiol Occup Physiol,* 55**,** 106-12.

NG, J. K. & RICHARDSON, C. A. 1996. Reliability of electromyographic power spectral analysis of back muscle endurance in healthy subjects. *Arch Phys Med Rehabil,* 77**,** 259-64.

NIELSEN, A. B. & YDE, J. 1989. Epidemiology and traumatology of injuries in soccer. *American Journal of Sports Medicine,* 17**,** 803-807.

NIELSEN, B. & NYBO, L. 2003. Cerebral changes during exercise in the heat. *Sports Med,* 33**,** 1-11.

NILSSON, J., TESCH, P. & THORSTENSSON, A. 1977. Fatigue and EMG of repeated fast voluntary contractions in man. *Acta Physiol Scand,* 101**,** 194-8.

NORMAN, R. W. & KOMI, P. V. 1979. Electromechanical delay in skeletal muscle under normal movement conditions. *Acta Physiol Scand,* 106**,** 241-8.

NOSAKA, K. & CLARKSON, P. M. 1997. Influence of previous concentric exercise on eccentric exercise-induced muscle damage. *J Sports Sci,* 15**,** 477-83.

NYBO, L. & SECHER, N. H. 2004. Cerebral perturbations provoked by prolonged exercise. *Prog Neurobiol,* 72**,** 223-61.

NYGAARD, E. 1981. Woman and exercise - with special reference to muscle morphology and metabolism. *In, Poortmans, J. and G. Niset (eds.), Biochemistry of exercise IV-B, Baltimore, University Park Press, 1981, p. 161-175.*

NYLAND, J. A., CABORN, D. N., SHAPIRO, R. & JOHNSON, D. L. 1997. Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surg Sports Traumatol Arthrosc,* 5**,** 162-7.

NYLAND, J. A., CABORN, D. N., SHAPIRO, R. & JOHNSON, D. L. 1999. Crossover cutting during hamstring fatigue produces transverse plane knee control deficits. *J Athl Train,* 34**,** 137-43.

NYLAND, J. A., SHAPIRO, R., STINE, R. L., HORN, T. S. & IRELAND, M. L. 1994. Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation. *J Orthop Sports Phys Ther,* 20**,** 132-7.

OLIPHANT, J. G. & DRAWBERT, J. P. 1996. Gender differences in anterior cruciate ligament injury rates in wisconsin intercollegiate basketball. *J Athl Train,* 31**,** 245-7.

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.

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., 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.

ORCHARD, J. W. & POWELL, J. W. 2003. Risk of knee and ankle sprains under various weather conditions in American football. *Medicine & Science in Sports & Exercise,* 35**,** 1118-1123.

OSTERNIG, L. R., CASTER, B. L. & JAMES, C. R. 1995. Contralateral hamstring (biceps femoris) coactivation patterns and anterior cruciate ligament dysfunction. *Med Sci Sports Exerc,* 27**,** 805-8.

PADUA, D. A., ARNOLD, B. L., PERRIN, D. H., GANSNEDER, B. M., CARCIA, C. R. & GRANATA, K. P. 2006. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train,* 41**,** 294-304.

PARK, K. S., CHOI, M. R., JUNG, K. H., KIM, S., KIM, H. Y., KIM, K. S., CHA, E. J., KIM, Y. & CHAI, Y. G. 2008. Diversity of ion channels in human bone marrow mesenchymal stem cells from amyotrophic lateral sclerosis patients. *Korean J Physiol Pharmacol,* 12**,** 337-42.

PASQUET, B., CARPENTIER, A., DUCHATEAU, J. & HAINAUT, K. 2000. Muscle fatigue during concentric and eccentric contractions. *Muscle Nerve,* 23**,** 1727-35.

PATTON, N. J. & MORTENSEN, O. A. 1971. An electromyographic study of reciprocal activity of muscles. *Anat Rec,* 170**,** 255-68.

PAUL, I. L., MUNRO, M. B., ABERNETHY, P. J., SIMON, S. R., RADIN, E. L. & ROSE, R. M. 1978. Musculo-skeletal shock absorption: Relative contribution of bone and soft tissues at various frequencies. *Journal of Biomechanics,* 11**,** 237-239.

PERRIN, D. H. 1993. Isokinetic Exercise and Assessment. *Human Kinetics Publishers, Champaign, IL.*

PERRIN, D. H. & SHULTZ, S. J. 2005. Physical Rehabilitation and the Challenge of Anterior Cruciate Ligament Injury in the Physically Active Female. *Quest (00336297),* 57**,** 154.

PINCIVERO, D. M., GANDAIO, C. M. & ITO, Y. 2003. Gender-specific knee extensor torque, flexor torque, and muscle fatigue responses during maximal effort contractions. *Eur J Appl Physiol,* 89**,** 134-41.

PINCIVERO, D. M., GEAR, W. S., STERNER, R. L. & KARUNAKARA, R. G. 2000. Gender differences in the relationship between quadriceps work and fatigue during high-intensity exercise. / Differences entre les sexes dans la relation entre le travail musculaire des quadriceps et la fatigue au cours d'un exercice de musculation de forte intensite. *Journal of Strength & Conditioning Research,* 14**,** 202-206.

PINCIVERO, D. M., LEPHART, S. M. & KARUNAKARA, R. A. 1997. Reliability and precision of isokinetic strength and muscular endurance for the quadriceps and hamstrings. *Int J Sports Med,* 18**,** 113-7.

PINNIGER, G. J., STEELE, J. R., THORSTENSSON, A. & CRESSWELL, A. G. 2000. Tension regulation during lengthening and shortening actions of the human soleus muscle. *Eur J Appl Physiol,* 81**,** 375-83.

PLAMONDON, A., MARCEAU, C., STAINTON, S. & DESJARDINS, P. 1999. Toward a better prescription of the prone back extension exercise to strengthen the back muscles. *Scand J Med Sci Sports,* 9**,** 226-32.

POLGAR, J., JOHNSON, M. A., WEIGHTMAN, D. & APPLETON, D. 1973. Data on fibre size in thirty-six human muscles: An autopsy study. *Journal of the Neurological Sciences,* 19**,** 307-318.

POLLARD, C. D., BRAUN, B. & HAMILL, J. 2006. Influence of gender, estrogen and exercise on anterior knee laxity. *Clinical Biomechanics,* 21**,** 1060-1066.

POUSSON, M., AMIRIDIS, I. G., COMETTI, G. & VAN HOECKE, J. 1999. Velocity-specific training in elbow flexors. *Eur J Appl Physiol Occup Physiol,* 80**,** 367-72.

POUSSON, M., PEROT, C. & GOUBEL, F. 1991. Stiffness changes and fibre type transitions in rat soleus muscle produced by jumping training. *Pflugers Arch,* 419**,** 127-30.

POWELL, J. W. & BARBER-FOSS, K. D. 2000. Sex-related injury patterns among selected high school sports. *Am J Sports Med,* 28**,** 385-91.

POWELL, K. E., KOHL, H. W., CASPERSEN, C. J. & BLAIR, S. N. 1986. An epidemiological perspective on the causes of running injuries. / Etude epidemilogique des risques lies a la course a pied. / Etude epidemiologique de la traumatologie de la course a pied. *Physician & Sportsmedicine,* 14**,** 100-103;106-108;111-114.

PULLMAN, S. L., GOODIN, D. S., MARQUINEZ, A. I., TABBAL, S. & RUBIN, M. 2000. Clinical utility of surface EMG: report of the therapeutics and technology assessment subcommittee of the American Academy of Neurology. *Neurology,* 55**,** 171-7.

RADIN, E. L. 1986. Role of muscles in protecting athletes from injury. *Acta Med Scand Suppl,* 711**,** 143-7.

RAHNAMA, N., REILLY, T., LEES, A. & GRAHAM-SMITH, P. 2003. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci,* 21**,** 933-42.

RAINOLDI, A., BULLOCK-SAXTON, J. E., CAVARRETTA, F. & HOGAN, N. 2001. Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects. *J Electromyogr Kinesiol,* 11**,** 425-38.

RAMPININI, E., IMPELLIZZERI, F. M., CASTAGNA, C., COUTTS, A. J. & WISLOFF, U. 2009. Technical performance during soccer matches of the Italian Serie A league: effect of fatigue and competitive level. *J Sci Med Sport,* 12**,** 227-33.

REDFERN, M. 1992. Functional muscle: effects on electromyographic output. In: Soderberg GL, ed. Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives. Cincinnati, OH: US Department of Health and Human Services, Public Health Service; 103-120. NIOSH publication 91-100.

REID, B., SLATER, C. R. & BEWICK, G. S. 1999. Synaptic vesicle dynamics in rat fast and slow motor nerve terminals. *J Neurosci,* 19**,** 2511-21.

RENSTROM, P., LJUNGQVIST, A., ARENDT, E., BEYNNON, B., FUKUBAYASHI, T., GARRETT, W., GEORGOULIS, T., HEWETT, T. E., JOHNSON, H., 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.
RIBEIRO, F., MOTA, J. & OLIVEIRA, J. 2007. Effect of exercise-induced fatigue on position sense of the knee in the elderly. *European Journal of Applied Physiology,* 99**,** 379-385.
RIEMANN, B. L. & LEPHART, S. M. 2002a. The sensorimotor system. Part I. The physiologic basis of functional joint stability. *Journal of Athletic Training,* 37**,** 71-79.
RIEMANN, B. L. & LEPHART, S. M. 2002b. The sensorimotor system. Part II. The role of proprioception in motor control and functional joint stability. *Journal of Athletic Training,* 37**,** 80-84.
RIZZARDO, M., BAY, G. & WESSEL, J. 1988. Eccentric and concentric torque and power of the knee extensors of females. *Canadian Journal of Sport Sciences,* 13**,** 166-169.
RIZZU, S., YUKTANANDANA, P., PINCIVERO, D. & LEPHART, S. M. 2000. Role of fatigue on proprioception and neuromuscular control. *In Proprioception and neuromuscular control in joint stability, Champaign, Ill., Human Kinetics, c2000, p.375-383.* United States.
ROBEY, J. M., BLYTH, C. S. & MUELLER, F. O. 1971. Athletic injuries. Application of epidemiologic methods. *Journal of the American Medical Association***,** 184-189.
ROBINSON, M. E., MAC MILLAN, M., O'CONNOR, P., FULLER, A. & CASSISI, J. E. 1991. Reproducibility of maximal versus submaximal efforts in an isometric lumbar extension task. *J Spinal Disord,* 4**,** 444-8.
RONALD, H., JOHN, P. M. & RONALD, C. 1998. Effect of movement velocity on the median frequency of the electromyographic activity of the quadriceps and hamstrings during isokinetic testing. *Isokinetics and Exercise Science,* 7**,** 75-78.
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.
ROTHSTEIN, J. 1985. Measurement and clinical practice: theory and application. In: Rothstein JM, ed. Measurement in Physical Theray. New York, NY: Churchill Livingstone;.
ROY, S. H., DE LUCA, C. J. & CASAVANT, D. A. 1989. Lumbar muscle fatigue and chronic lower back pain. *Spine (Phila Pa 1976),* 14**,** 992-1001.
ROZZI, S. L., LEPHART, S. M. & FU, F. H. 1999a. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *Journal of Athletic Training,* 34**,** 106-114.
ROZZI, S. L., LEPHART, S. M., GEAR, W. S. & FU, F. H. 1999b. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. / Laxite de l'articulation du genou et caracteristiques neuromusculaires de joueurs et joueuses de football et de basketball. *American Journal of Sports Medicine,* 27**,** 312-319.
RUSS, D. W. & KENT-BRAUN, J. A. 2003. Sex differences in human skeletal muscle fatigue are eliminated under ischemic conditions. *J Appl Physiol,* 94**,** 2414-22.
RUSS, D. W., LANZA, I. R., ROTHMAN, D. & KENT-BRAUN, J. A. 2005. Sex differences in glycolysis during brief, intense isometric contractions. *Muscle Nerve,* 32**,** 647-55.
RUSS, D. W., TOWSE, T. F., WIGMORE, D. M., LANZA, I. R. & KENT-BRAUN, J. A. 2008. Contrasting influences of age and sex on muscle fatigue. *Med Sci Sports Exerc,* 40**,** 234-41.
RUSSELL, P. J., CROCE, R. V., SWARTZ, E. E. & DECOSTER, L. C. 2007. Knee-muscle activation during landings: developmental and gender comparisons. *Med Sci Sports Exerc,* 39**,** 159-70.
RYTOKOSKI, U., KARPPI, S.L., PUUKA, P., SOINI, J., AND RONNEMAA, T. 1994. Measurement of low back mobility, isometric strength and isominertial performance

with isostation B-200 triaxial dynamometer: reporoducibility of measurement and development of functional indicies. *J. Spinal Disord.*, 1.

SALE, D., QUINLAN, J., MARSH, E., MCCOMAS, A. J. & BELANGER, A. Y. 1982. Influence of joint position on ankle plantarflexion in humans. *J Appl Physiol,* 52**,** 1636-42.

SAMUEL, C. S., BUTKUS, A., COGHLAN, J. P. & BATEMAN, J. F. 1996. The effect of relaxin on collagen metabolism in the nonpregnant rat pubic symphysis: the influence of estrogen and progesterone in regulating relaxin activity. *Endocrinology,* 137**,** 3884-90.

SAPEGA, A. A. 1990. Muscle performance evaluation in orthopaedic practice. *J Bone Joint Surg Am,* 72**,** 1562-74.

SAPEGA, A. A., NICHOLAS, J. A., SOKOLOW, D. & SARANITI, A. 1982. Nature of torque "overshoot" in Cybex isokinetic dynamometry. *Medicine & Science in Sports & Exercise,* 14**,** 368-375.

SAURET, J., DE STE CROIX, M., DEIGHAN, M., IGA, J. & JAMES, D. 2009. Reproducibility of an isokinetic eccentric muscle endurance task. *European Journal of Sport Science,* 9**,** 311-319.

SCHILLINGS, M. L., HOEFSLOOT, W., STEGEMAN, D. F. & ZWARTS, M. J. 2003. Relative contributions of central and peripheral factors to fatigue during a maximal sustained effort. *Eur J Appl Physiol,* 90**,** 562-8.

SEGER & THORSTENSSON 2000. Electrically evoked eccentric and concentric torque–velocity relationships in human knee extensor muscles. *Acta Physiologica Scandinavica,* 169**,** 63-69.

SELL, T., FERRIS, C. M., ABT, J. P., TSAI, Y. S., JOSEPH, M. B., FU, F. H. & LEPHART, S. M. 2004. Predictors of anterior tibia shear force during a vertical stop-jump. (Abstract). *Journal of Orthopaedic & Sports Physical Therapy,* 34**,** A56-A56.

SENTER, C. & HAME, S. L. 2006. Biomechanical analysis of tibial torque and knee flexion angle: implications for understanding knee injury. *Sports Med,* 36**,** 635-41.

SHARKEY, N. A., FERRIS, L., SMITH, T. S. & MATTHEWS, D. K. 1995. Strain and loading of the second metatarsal during heel-lift. *J Bone Joint Surg Am,* 77**,** 1050-7.

SHELBOURNE, K. D., DAVIS, T. J. & KLOOTWYK, T. E. 1998. The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears: a prospective study. *American Journal of Sports Medicine,* 26**,** 402-408.

SHI, Z. 1996. Acute effect of repeated maximal isometric contraction on electromechanical delay of knee extensor muscle. *Journal of Electromyography and Kinesiology,* 6**,** 117-127.

SHIELD, A. & ZHOU, S. 2004. Assessing voluntary muscle activation with the twitch interpolation technique. *Sports Med,* 34**,** 253-67.

SHORTEN, M. R. 1987. Muscle elasticity and human performance. *In, Gheluwe, B. van, and Atha, J. (eds.), Current research in sports biomechanics, Basel, Karger, 1987, p. 1-18.* Switzerland.

SHULTZ, S. J. & PERRIN, D. H. 1999. Using surface electromyography to assess sex differences in neuromuscular response characteristics. *J Athl Train,* 34**,** 165-76.

SIECK, G. C., HAN, Y. S., PRAKASH, Y. S. & JONES, K. A. 1998. Cross-bridge cycling kinetics, actomyosin ATPase activity and myosin heavy chain isoforms in skeletal and smooth respiratory muscles. *Comp Biochem Physiol B Biochem Mol Biol,* 119**,** 435-50.

SITLER, M., RYAN, C. J., HOPKINSON, W., WHEELER, J., SANTOMIER, J., KOLB, R. & POLLEY, D. 1990. The efficacy of a prophylactic knee brace to reduce knee injuries in football. A prospective, randomized study at West Point. / L ' efficacite d ' une genouillere pour reduire les lesions du genou en football americain. *American Journal of Sports Medicine,* 18**,** 310-315.

SJOGAARD, G. & MCCOMAS, A. J. 1995. Role of interstitial potassium. *Adv Exp Med Biol,* 384**,** 69-80.

SJOLANDER, P., JOHANSSON, H. & DJUPSJOBACKA, M. 2002. Spinal and supraspinal effects of activity in ligament afferents. *Journal of Electromyography & Kinesiology,* 12**,** 167-176.

SKINNER, H. B., WYATT, M. P., HODGDON, J. A., CONARD, D. W. & BARRACK, R. L. 1986. Effect of fatigue on joint position sense of the knee. *J Orthop Res,* 4**,** 112-8.

SLAUTERBECK, J., CLEVENGER, C., LUNDBERG, W. & BURCHFIELD, D. M. 1999. Estrogen level alters the failure load of the rabbit anterior cruciate ligament. *J Orthop Res,* 17**,** 405-8.

SLAUTERBECK, J. R., FUZIE, S. F., SMITH, M. P., CLARK, R. J., XU, K., STARCH, D. W. & HARDY, D. M. 2002a. The Menstrual Cycle, Sex Hormones, and Anterior Cruciate Ligament Injury. *J Athl Train,* 37**,** 275-278.

SLAUTERBECK, J. R., FUZIE, S. F., SMITH, M. P., CLARK, R. J., XU, K. T., STARCH, D. W. & HARDY, D. M. 2002b. The menstrual cycle, sex hormones, and anterior cruciate ligament injury. *Journal of Athletic Training,* 37**,** 275-280.

SMALL, K., MCNAUGHTON, L., GREIG, M. & LOVELL, R. 2010. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *J Sci Med Sport,* 13**,** 120-5.

SMIDT, G., HERRING, T., AMUNDSEN, L., ROGERS, M., RUSSELL, A. & LEHMANN, T. 1983. Assessment of abdominal and back extensor function. A quantitative approach and results for chronic low-back patients. *Spine (Phila Pa 1976),* 8**,** 211-9.

SMITH, B. A., LIVESAY, G. A. & WOO, S. L. Y. 1993. Biology and biomechanics of the anterior cruciate ligament. *Clinics in Sports Medicine,* 12**,** 637-670.

SMITH, J. L., MARTIN, P. G., GANDEVIA, S. C. & TAYLOR, J. L. 2007. Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles. *J Appl Physiol,* 103**,** 560-8.

SODERBERG, G. L. & COOK, T. M. 1984. Electromyography in biomechanics. *Phys Ther,* 64**,** 1813-20.

SODERBERG, G. L. & KNUTSON, L. M. 2000. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther,* 80**,** 485-98.

SOLOMONOW, M., BARATTA, R. & D'AMBROSIA, R. 1989. The role of the hamstrings in the rehabilitation of the anterior cruciate ligament-deficient knee in athletes. *Sports Med,* 7**,** 42-8.

SOLOMONOW, M., BARATTA, R., ZHOU, B. H., SHOJI, H., BOSE, W., BECK, C. & D'AMBROSIA, R. 1987. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. / Action synergique du ligament croise anterieur et des muscles des cuisses dans le maintien de la stabilite de l ' articulation. *American Journal of Sports Medicine,* 15**,** 207-213.

SOLOMONOW, M. & KROGSGAARD, M. 2001. Sensorimotor control of knee stability. A review. / Controle sensorimoteur de la stabilite du genou: revue. *Scandinavian Journal of Medicine & Science in Sports,* 11**,** 64-80.

SOMJEN, G., CARPENTER, D. O. & HENNEMAN, E. 1965. Responses of motoneurons of different sizes to graded stimulation of supraspinal centers of the brain. *J Neurophysiol,* 28**,** 958-65.

SORENSEN, H., ZACHO, M., SIMONSEN, E. B., DYHRE-POULSEN, P. & KLAUSEN, K. 1998. Joint angle errors in the use of isokinetic dynamometers. *Isokinetics & Exercise Science,* 7**,** 129.

SPENDIFF, O., LONGFORD, N. T. & WINTER, E. M. 2002. Effects of fatigue on the torque-velocity relation in muscle. *Br J Sports Med,* 36**,** 431-5.

STAFFORD, M. G. & GRANA, W. A. 1984. Hamstring/quadriceps ratios in college football players: a high velocity evaluation. *Am J Sports Med,* 12**,** 209-11.

STANTON, P. & PURDAM, C. 1989. Hamstring injuries in sprinting: the role of eccentric exercise. *Journal of Orthopaedic & Sports Physical Therapy,* 10**,** 343-349.

STEINER, L. A., HARRIS, B. A. & KREBS, D. E. 1993. Reliability of eccentric isokinetic knee flexion and extension measurement. *Archives of Physical Medicine & Rehabilitation,* 74**,** 1327-1335.
STROJNIK, V. & KOMI, P. V. 1998. Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *J Appl Physiol,* 84**,** 344-50.
SULLIVAN, J. A., GROSS, R. H., GRANA, W. A. & GARCIAS-MORAL, C. A. 1980. Evaluation of injuries in youth soccer. / Evaluation des blessures subies par les jeunes footballeurs. *American Journal of Sports Medicine,* 8**,** 325-327.
TALBOT, J. A. & MORGAN, D. L. 1998. The effects of stretch parameters on eccentric exercise-induced damage to toad skeletal muscle. *J Muscle Res Cell Motil,* 19**,** 237-45.
TAYLOR, A. D., BRONKS, R., SMITH, P. & HUMPHRIES, B. 1997a. Myoelectric evidence of peripheral muscle fatigue during exercise in severe hypoxia: some references to m. vastus lateralis myosin heavy chain composition. *Eur J Appl Physiol Occup Physiol,* 75**,** 151-9.
TAYLOR, A. D., HUMPHRIES, B., SMITH, P. & BRONKS, R. 1997b. Electrophoretic separation of myosin heavy chain isoforms in the human m. vastus lateralis: references to reproducibility and relationships with force, electromechanical delay, fibre conduction velocity, endurance and electromyography. *Arch Physiol Biochem,* 105**,** 10-8.
TAYLOR, J. L., BUTLER, J. E. & GANDEVIA, S. C. 1999. Altered responses of human elbow flexors to peripheral-nerve and cortical stimulation during a sustained maximal voluntary contraction. *Exp Brain Res,* 127**,** 108-15.
TAYLOR, J. L. & GANDEVIA, S. C. 2008. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol,* 104**,** 542-50.
TAYLOR, J. L., TODD, G. & GANDEVIA, S. C. 2006. Evidence for a supraspinal contribution to human muscle fatigue. *Clin Exp Pharmacol Physiol,* 33**,** 400-5.
TEITZ, C. 2001. Video analysis of ACL injuries. In: Griffin LY, ed. Prevention of noncontact ACL injuries. Rosemont, IL. *American Association of Orthopaedic Surgeons***,** 87–92.
THOMPSON, B. J., SMITH, D. B., SOBOLEWSKI, E. J., FIDDLER, R. E., EVERETT, L., KLUFA, J. L. & RYAN, E. D. 2011. Influence of acute eccentric exercise on the h:q ratio. *Int J Sports Med,* 32**,** 935-9.
TIIDUS, P. M. & IANUZZO, C. D. 1983. Effects of intensity and duration of muscular exercise on delayed soreness and serum enzyme activities. *Med Sci Sports Exerc,* 15**,** 461-5.
TOURNY-CHOLLET, C. & LEROY, D. 2002. Conventional vs. dynamic hamstring-quadriceps strength ratios: A comparison between players and sedentary subjects. *Isokinetics & Exercise Science,* 10**,** 183.
TREDINNICK, T. J. & DUNCAN, P. W. 1988. Reliability of measurements of concentric and eccentric isokinetic loading. *Physical Therapy,* 68**,** 656-659.
UHORCHAK, J. M., SCOVILLE, C. R., WILLIAMS, G. N., ARCIERO, R. A., ST. PIERRE, P. & TAYLOR, D. C. 2003. Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. *American Journal of Sports Medicine,* 31**,** 831-842.
URQUHART, D. S., GARBUTT, G., COVA, K., LENNOX, C. M. E. & MCLATCHIE, G. R. 1995. Isokinetics: applications in the management of knee soft-tissue injuries. *Sports Exercise & Injury,* 1**,** 138-147.
VAN INGEN SCHENAU, G. J., BOOTS, P. J. M., DE GROOT, G., SNACKERS, R. J. & VAN WOENSEL, W. W. L. M. 1992. The constrained control of force and position in multi-joint movements. *Neuroscience,* 46**,** 197-207.
VAN MECHELEN, W., HLOBIL, H. & KEMPER, H. C. G. 1992. Incidence, severity, aetiology and prevention of sports injuries : a review of concepts (Incidence, gravite, etiologie et prevention des traumatismes sportifs : une revue de concepts). *Sports Medicine,* 14**,** 82-99.

VERDONCK, A., FROBOSE, I., HARDELAUF, U. & GUTTGE, C. 1994. Contraction patterns during isokinetic eccentric and concentric contractions after anterior cruciate ligament injury. *Int J Sports Med,* 15 Suppl 1**,** S60-3.

VIITASALO, J. & KOMI, P. 1980. EMG, Reflex and Reaction Time Components, Muscle Structure, and Fatigue During Intermittent Isometric Contractions in Man. *International Journal of Sports Medicine,* 1**,** 185-190.

VIITASALO, J. H. & KOMI, P. V. 1977. Signal characteristics of EMG during fatigue. *Eur J Appl Physiol Occup Physiol,* 37**,** 111-21.

VIITASALO, J. T. & KOMI, P. V. 1981. Interrelationships between electromyographic, mechanical, muscle structure and reflex time measurements in man. *Acta Physiol Scand,* 111**,** 97-103.

VINCENT, J. M. 1995. Comparing means of two groups sets of data In: Statistics in Kinesiology, Champaign, IL: Kinetics, pp 115-145.

VØLLESTAD, N. K. 1997. Measurement of human muscle fatigue. *Journal of Neuroscience Methods,* 74**,** 219-227.

VOLLESTAD, N. K., SEJERSTED, O. M., BAHR, R., WOODS, J. J. & BIGLAND-RITCHIE, B. 1988. Motor drive and metabolic responses during repeated submaximal contractions in humans. *J Appl Physiol,* 64**,** 1421-7.

VOS, E. J., HARLAAR, J. & VAN INGEN SCHENAU, G. J. 1991. Electromechanical delay during knee extensor contractions. *Med Sci Sports Exerc,* 23**,** 1187-93.

WALMSLEY, B., HODGSON, J. A. & BURKE, R. E. 1978. Forces produced by medial gastrocnemius and soleus muscles during locomotion in freely moving cats. *Journal of neurophysiology,* 41**,** 1203-16.

WARREN, G. L., HERMANN, K. M., INGALLS, C. P., MASSELLI, M. R. & ARMSTRONG, R. B. 2000. Decreased EMG median frequency during a second bout of eccentric contractions. *Med Sci Sports Exerc,* 32**,** 820-9.

WARREN, G. L., LOWE, D. A. & ARMSTRONG, R. B. 1999. Measurement tools used in the study of eccentric contraction-induced injury. *Sports Med,* 27**,** 43-59.

WARREN, G. L., LOWE, D. A., HAYES, D. A., KARWOSKI, C. J., PRIOR, B. M. & ARMSTRONG, R. B. 1993. Excitation failure in eccentric contraction-induced injury of mouse soleus muscle. *J Physiol,* 468**,** 487-99.

WATT, P. W., KELLY, F. J., GOLDSPINK, D. F. & GOLDSPINK, G. 1982. Exercise-induced morphological and biochemical changes in skeletal muscles of the rat. *J Appl Physiol,* 53**,** 1144-51.

WEIR, J. P., EVANS, S. A. & HOUSH, M. L. 1996. The effect of extraneous movements on peak torque and constant joint angle torque-velocity curves. *Journal of Orthopaedic & Sports Physical Therapy,* 23**,** 302-308.

WEISMAN, G., POPE, M. H. & JOHNSON, R. J. 1980. Cyclic loading in knee ligament injuries. *Am J Sports Med,* 8**,** 24-30.

WESTERBLAD, H., LEE, J. A., LANNERGREN, J. & ALLEN, D. G. 1991. Cellular mechanisms of fatigue in skeletal muscle. *Am J Physiol,* 261**,** C195-209.

WESTING, S. H. & SEGER, J. Y. 1989. Eccentric and concentric torque-velocity characteristics, torque output comparisons, and gravity effect torque corrections for the quadriceps and hamstring muscles in females. *International Journal of Sports Medicine,* 10**,** 175-80.

WESTING, S. H., SEGER, J. Y. & THORSTENSSON, A. 1990. Effects of electrical stimulation on eccentric and concentric torque-velocity relationships during knee extension in man. *Acta Physiol Scand,* 140**,** 17-22.

WHITE, K. K., LEE, S. S., CUTUK, A., HARGENS, A. R. & PEDOWITZ, R. A. 2003. EMG power spectra of intercollegiate athletes and anterior cruciate ligament injury risk in females. *Medicine & Science in Sports & Exercise,* 35**,** 371-376.

WIKSTROM, E. A., ARRIGENNA, M. A., TILLMAN, M. D. & BORSA, P. A. 2006. Dynamic postural stability in subjects with braced, functionally unstable ankles. *J Athl Train,* 41**,** 245-50.

WIKSTROM, E. A., POWERS, M. E. & TILLMAN, M. D. 2004. Dynamic Stabilization Time After Isokinetic and Functional Fatigue. *J Athl Train,* 39**,** 247-253.

WILHITE, M. R., COHEN, E. R. & WILHITE, S. C. 1992. Reliability of Concentric and Eccentric Measurements of Quadriceps Performance Using the KIN-COM Dynamometer: The Effect of Testing Order for Three Different Speeds. *J Orthop Sports Phys Ther,* 15**,** 175-82.

WILK, K. E., ROMANIELLO, W. T., SOSCIA, S. M., ARRIGO, C. A. & ANDREWS, J. R. 1994. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther,* 20**,** 60-73.

WILLIAMS, G. N., CHMIELEWSKI, T., RUDOLPH, K. S., BUCHANAN, T. S. & SNYDER-MACKLER, L. 2001. Dynamic knee stability: current theory and implications for clinicians and scientists. *Journal of Orthopaedic & Sports Physical Therapy,* 31**,** 546-566.

WILSON, G. J., MURPHY, A. J. & PRYOR, J. F. 1994. Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. *J Appl Physiol,* 76**,** 2714-9.

WINTER, D., RAU, G., KADEFORS, R., BROMAN, H. & DELUCA, C. 1980. Units, Terms and Standards in the Reporting of EMG Research. Boston, MA: International Society of Electrophysiological Kinesiology.

WINTER, D. A. 1991. Electromyogram recording, processing, and normalization: procedures and considerations. *Journal of Human Muscle Performance,* 1**,** 5-15.

WINTER, D. A., WELLS, R. P. & ORR, G. W. 1981. Errors in the use of isokinetic dynamometers. *Eur J Appl Physiol Occup Physiol,* 46**,** 397-408.

WINTER, E. M. & BROOKES, F. B. 1991. Electromechanical response times and muscle elasticity in men and women. *Eur J Appl Physiol Occup Physiol,* 63**,** 124-8.

WOJTYS, E. M., HUSTON, L. J., BOYNTON, M. D., SPINDLER, K. P. & LINDENFELD, T. N. 2002b. The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *Am J Sports Med,* 30**,** 182-8.

WOJTYS, E. M., HUSTON, L. J., LINDENFELD, T. N., HEWETT, T. E. & GREENFIELD, M. L. 1998. Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *Am J Sports Med,* 26**,** 614-9.

WOJTYS, E. M., HUSTON, L. J., TAYLOR, P. D. & BASTIAN, S. D. 1996a. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *Am J Sports Med,* 24**,** 187-92.

WOJTYS, E. M., WYLIE, B. B. & HUSTON, L. J. 1996b. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am J Sports Med,* 24**,** 615-21.

WOLEDGE, R. C., CURTIN, N. A. & HOMSHER, E. 1985. Energetic aspects of muscle contraction. *Monographs of the Physiological Society,* 41**,** 1-357.

WORRELL, T. W., DENEGAR, C. R., ARMSTRONG, S. L. & PERRIN, D. H. 1990. Effect of body position on hamstring muscle group average torque. *Journal of Orthopaedic & Sports 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.

WU, L. G. & BETZ, W. J. 1998. Kinetics of synaptic depression and vesicle recycling after tetanic stimulation of frog motor nerve terminals. *Biophys J,* 74**,** 3003-9.

WYATT, M. P. & EDWARDS, A. M. 1981. Comparison of quadriceps and hamstring torque values during isokinetic exercise. *Journal of Orthopaedic & Sports Physical Therapy,* 3**,** 48-56.

WYSE, J. P., MERCER, T. H. & GLEESON, N. P. 1994. Time-of-day dependence of isokinetic leg strength and associated interday variability. *Br J Sports Med,* 28**,** 167-70.

YANG, J. F. & WINTER, D. A. 1983. Electromyography reliability in maximal and submaximal isometric contractions. *Arch Phys Med Rehabil,* 64**,** 417-20.

YASUDA, K. & SASAKI, T. 1987. Muscle exercise after anterior cruciate ligament reconstruction. Biomechanics of the simultaneous isometric contraction method of the quadriceps and the hamstrings. *Clinical Orthopaedics & Related Research***,** 266-274.

YAVUZ, S. U., SENDEMIR-ÜRKMEZ, A. & TÜRKER, K. S. 2010. Effect of gender, age, fatigue and contraction level on electromechanical delay. *Clinical Neurophysiology,* 121**,** 1700-1706.

YEADON, M. R., KING, M. A. & WILSON, C. 2006. Modelling the maximum voluntary joint torque/angular velocity relationship in human movement. *J Biomech,* 39**,** 476-82.

YEUNG, S. S., AU, A. L. & CHOW, C. C. 1999. Effects of fatigue on the temporal neuromuscular control of vastus medialis muscle in humans. *European Journal of Applied Physiology and Occupational Physiology,* 80**,** 379-385.

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.

YOON, T. S., PARK, D. S., KANG, S. W., CHUN, S. I. & SHIN, J. S. 1991. Isometric and isokinetic torque curves at the knee joint. *Yonsei Med J,* 32**,** 33-43.

YU, B. & GARRETT, W. E. 2007. Mechanisms of non-contact ACL injuries. *British Journal of Sports Medicine,* 41**,** i47-i51.

YU, B., HERMAN, D., PRESTON, J., LU, W., KIRKENDALL, D. T. & GARRETT, W. E. 2004. Immediate Effects of a Knee Brace With a Constraint to Knee Extension on Knee Kinematics and Ground Reaction Forces in a Stop-Jump Task. *American Journal of Sports Medicine,* 32**,** 1136-1143.

ZAZULAK, B. T., PONCE, P. L., STRAUB, S. J., MEDVECKY, M. J., AVEDISIAN, L. & HEWETT, T. E. 2005. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther,* 35**,** 292-9.

ZELISKO, J. A., NOBLE, H. B. & PORTER, M. 1982. A comparison of men's and women's professional basketball injuries. *Am J Sports Med,* 10**,** 297-9.

ZHOU, S., CAREY, M. F., SNOW, R. J., LAWSON, D. L. & MORRISON, W. E. 1998. Effects of muscle fatigue and temperature on electromechanical delay. *Electromyogr Clin Neurophysiol,* 38**,** 67-73.

ZHOU, S., LAWSON, D. L., MORRISON, W. E. & FAIRWEATHER, I. 1995. Electromechanical delay in isometric muscle contractions evoked by voluntary, reflex and electrical stimulation. *Eur J Appl Physiol Occup Physiol,* 70**,** 138-45.

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. *Eur J Appl Physiol Occup Physiol,* 72**,** 410-6.

ZILLMER, E. A., WAECHTLER, C., HARRIS, B., KHAN, F. & FOWLER, P. C. 1992. The effects of unilateral and multifocal lesions on the WAIS-R: a factor analytic study of stroke patients. *Arch Clin Neuropsychol,* 7**,** 29-40.

Appendix (1)

Statistical power calculations for sample size

Sample size estimation based on the FH/Q ratio production at 60, 120 and 240°·s^{-1} to distinguish the minimum clinically important difference from the statistical null with an alpha level of 0.05.

Power	Variables: FH/Q ratios	SD values at each angular velocities			Δ^2 values at each angular velocities			Sample size at each angular velocities		
		60°·s^{-1}	120°·s^{-1}	240°·s^{-1}	60°·s^{-1}	120°·s^{-1}	240°·s^{-1}	60°·s^{-1}	120°·s^{-1}	240°·s^{-1}
0.8	FH/Q ratio at 15°	14	13	19	13	14	19	157	58	200
	FH/Q ratio at 30°	13	13	12	8	9	11	101	270	94
	FH/Q ratio at 45°	10	13	10	8	6	17	60	221	206
	FH/Q ratio PT	9	11	13	8	8	18	90	158	203
0.5	FH/Q ratio at 15°	14	13	19	13	14	19	65	24	83
	FH/Q ratio at 30°	13	13	12	8	9	11	42	113	39
	FH/Q ratio at 45°	10	13	10	8	6	17	25	92	86
	FH/Q ratio PT	9	11	13	8	8	18	37	66	84

Sample size estimation based on the EMD production at 60, 120 and 240°·s^{-1} to distinguish the minimum clinically important difference from the statistical null with an alpha level of 0.05.

Power	Variables: EMD of hamstrings muscle	SD values for each angular velocities			Δ^2 values for each angular velocities			Sample size at each angular velocities		
		60°·s^{-1}	120°·s^{-1}	240°·s^{-1}	60°·s^{-1}	120°·s^{-1}	240°·s^{-1}	60°·s^{-1}	120°·s^{-1}	240°·s^{-1}
0.8	EMD of BF	3.9	12.6	9.3	2	3	5	24	208	125
	EMD of SM	3.9	12.3	10.4	2	3	5	73	311	120
	EMD of ST	4.4	13.2	9.2	2	3	3	56	105	122
	Max of EMD	3.4	11.2	7.6	2	4	4	42	452	166
0.5	EMD of BF	3.9	12.6	9.3	2	3	5	10	87	52
	EMD of SM	3.9	12.3	10.4	2	3	5	30	130	50
	EMD of ST	4.4	13.2	9.2	2	3	3	23	44	51
	Max of EMD	3.4	11.2	7.6	2	4	4	17	188	69

Note: sample size estimation formula: $N = \frac{2SD^2\,(Z\propto + Z\beta)^2}{\Delta^2}$

$Z\propto$ = Alpha level (0.05).

$Z\beta$ = Power.

Δ^2 = The difference between the two mean values being compared.

SD = The standard deviation of the two groups.

N = Approximate sample size estimated.

Appendix (2)

(Information sheet for participants)

The functional hamstring to quadriceps ratio and neuromuscular performance

Dear participant

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

What is the project about?

We are interested in looking at sex differences in the FH/Q and neuromuscular functioning of the knee joint muscles that appear to be associated with an increased risk of non-contact ACL injury in females in both a fatigued and non-fatigued state.

Who is taking part in the study?

We need 100 subjects (50 males and 50 females, age: 18-40) or more to take part in the project.

What will I be asked to do?

If you volunteer for this study we will ask you to perform a repeated active kicking action on a type of strength machine called an isokinetic dynamometer. You should complete a familiarization protocol in order to prepare for all testing protocols (1 session) before start the study. In total you would need to come to the laboratory on 3 separate occasions for about 40min each time. During three laboratory trials, each subject will complete this sequence of activities:

- Laboratory session 1: habituation (max 45 min)
- Laboratory session 2: pre-fatigue trial: PT assessments during concentric quadriceps and eccentric hamstrings action at three angular velocities (using the isokinetic dynamometer and the surface EMG unit). (40min)
- Laboratory session 3: fatigue protocol and repeat of session 2: This consists of a 40 min intermittent bout of 5 × 8 min downhill running exercise on a treadmill. (80min)
- One week of separation will be between each laboratory trials.

When will I do it?

Whenever you are available and the laboratory is available we will arrange a time for you to come to the laboratory. If you wish to come as a group or with friends that may be possible (maximum of 2 people). All tests will take place at the University of Gloucestershire and will follow our laboratory procedures guidelines.

Can I change my mind?

You can stop being in the study at any time. This will not affect your relationship with the research team or the university.

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 Research team. You name will never be used.

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.

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Department of Sports and Exercise Sciences.

PhD Research student

University of Gloucestershire

Dr Mark De Ste Croix

Faculty Research Director

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Appendix (3)

SPORT & EXERCISE LABORATORIES

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

Name: …………………………………………

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

Tester: ………………………………………..

Appendix (4)

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 or absorbing high forces through your shoulders	☐
Cycling	☐	Generating or absorbing high forces through your trunk	☐
Rowing	☐	Generating or absorbing high forces through your hips	☐
Swimming	☐	Generating or 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

f)

(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) No Yes

for 20 minutes or longer at least twice a week?

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) No Yes

at least once a week?

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 Ye

   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, No Yes

   other lung disease, liver disease, kidney disease, mental illness,

   osteoporosis, severe arthritis, a thyroid problem?

(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	Yes
13.	Do you experience swelling or a build up 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? No Yes

    a) I smoke cigarettes on a daily basis
    b) I stopped smoking cigarettes on a daily basis less than 6 months ago
    c)

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? No Yes

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

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)

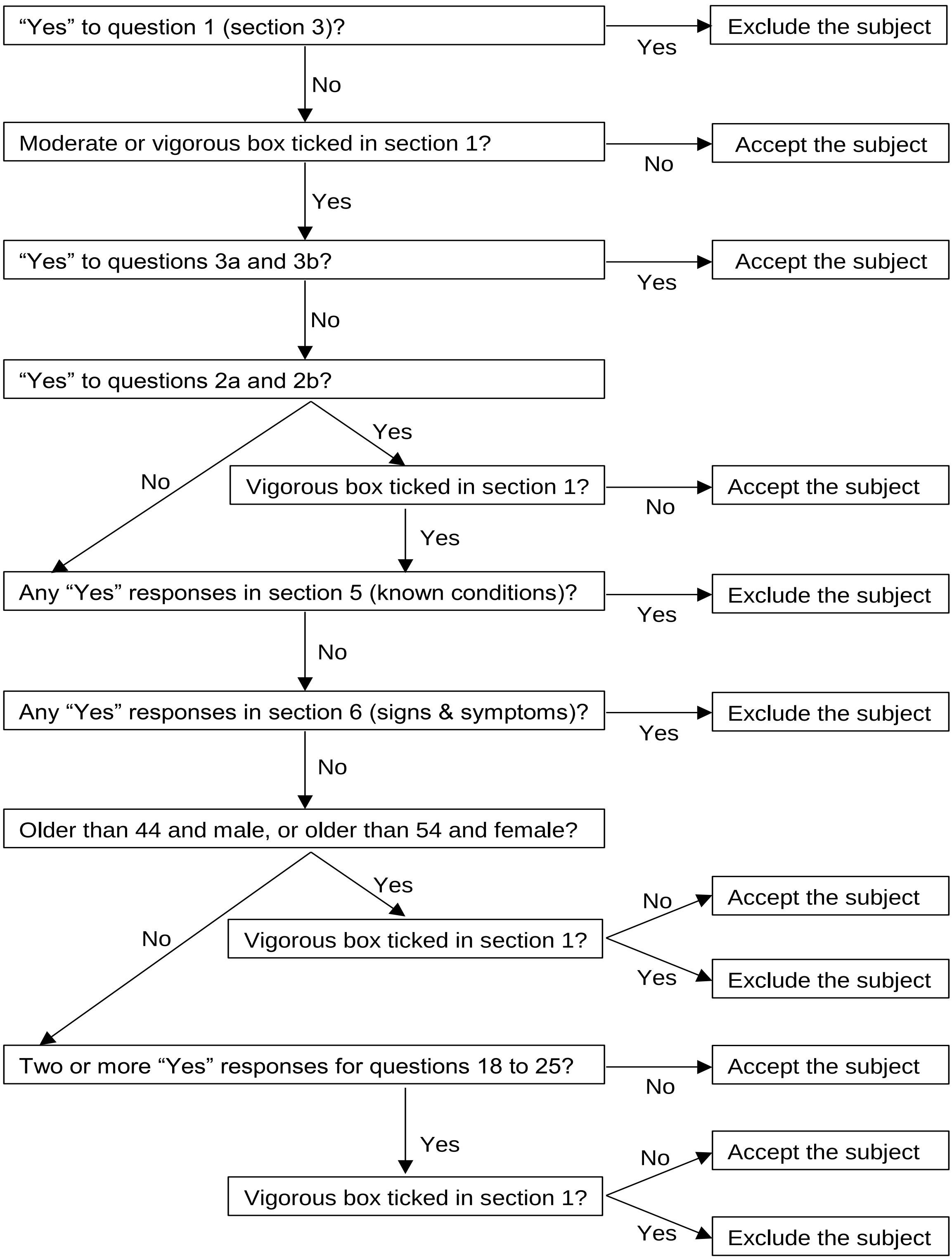
26. Is the participant eligible for the testing? No Yes

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

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

Appendix (5)

Processing the completed questionnaire – a flow diagram



Appendix (6)

FH/Q ratio and EMD values of male's participants and females (pre-post fatigue):

1- FH/Q Ratio Values of male's participants (pre-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT
1	92	82	61	57	84	86	81	84	98	109	97	95
2	71	67	52	54	94	100	62	70	121	110	96	81
3	81	98	75	77	83	89	60	82	118	110	97	80
4	96	79	74	73	83	98	76	68	114	109	97	95
5	73	62	75	56	93	95	70	62	123	88	97	93
6	82	83	66	64	78	91	74	74	109	107	97	95
7	63	91	75	73	86	105	87	83	73	108	97	85
8	81	97	81	71	84	104	67	54	82	108	97	93
9	79	80	65	65	73	66	86	60	119	109	97	95
10	84	61	73	64	70	99	89	70	92	109	97	82
11	77	69	78	80	93	75	70	67	123	108	98	101
12	89	83	54	59	98	96	82	85	125	110	96	75
13	66	82	74	76	98	78	79	82	119	110	96	90
14	80	91	79	67	84	107	100	86	85	107	97	91
15	84	66	75	67	92	103	96	84	84	111	97	92
16	86	70	72	57	93	112	75	61	118	107	114	93
17	81	88	65	71	88	90	84	64	102	108	97	91
18	91	81	59	65	89	105	93	75	75	90	97	94
19	60	97	74	73	83	105	78	79	113	110	97	96
20	68	91	65	65	100	69	59	54	102	110	97	84
21	69	70	71	59	100	107	67	83	127	137	96	78
22	89	72	72	67	84	101	71	72	123	108	96	90
23	71	84	82	75	80	108	94	48	91	107	98	89
24	73	76	76	58	96	86	65	82	76	108	97	73
25	85	68	66	65	83	85	92	54	120	125	96	68
26	76	75	56	59	91	103	61	52	115	110	97	77
27	62	60	66	74	100	77	75	77	84	110	97	88

28	64	75	78	72	72	108	79	80	127	107	68	90
29	88	95	71	67	84	112	96	67	84	110	97	96
30	75	93	76	73	79	86	76	85	100	109	96	81
31	95	89	71	73	96	75	99	70	92	131	97	90
32	78	78	71	61	98	108	68	62	90	108	97	91
33	77	99	83	79	72	83	99	81	124	109	97	92
34	77	98	76	63	98	89	63	65	93	108	96	93
35	90	93	66	70	90	89	99	83	105	79	96	81
36	61	83	75	60	98	109	92	76	82	87	97	84
37	64	83	70	71	86	82	77	81	126	110	97	92
38	80	66	46	51	98	94	53	76	84	111	97	94
39	73	80	70	71	96	84	64	67	118	109	96	94
40	79	90	71	69	76	63	64	65	137	109	97	97
41	80	55	74	67	98	87	79	87	124	109	96	97
42	62	62	75	57	93	105	70	85	77	110	97	75
43	53	93	67	70	81	91	60	79	102	137	96	72
44	95	89	65	64	94	100	57	79	80	108	97	90
45	48	73	67	74	68	94	60	58	89	110	96	75
46	64	83	76	69	92	109	80	69	107	108	97	79
47	66	81	58	58	93	102	92	77	89	110	96	74
48	67	58	63	61	79	94	84	72	112	110	97	79
49	69	82	72	61	89	79	96	81	102	108	96	74
50	84	87	61	55	83	92	98	88	71	108	98	85
51	67	73	59	58	100	89	94	74	110	111	97	82
52	68	70	78	67	84	94	91	73	111	108	96	74
53	84	87	73	54	88	91	94	80	122	108	96	92
54	54	83	74	73	100	111	92	75	119	109	97	93
55	51	61	76	76	81	106	87	81	100	81	97	93
Mean:	75	80	70	66	88	94	79	73	104	109	97	87
SD:	11.7	11.7	7.8	7.2	8.8	12.2	13.5	10.2	17.7	9.9	4.5	8.2

2- FH/Q Ratio Values of female's participants (pre-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT
1	75	92	55	55	74	67	79	59	118	84	85	84
2	73	78	51	53	59	83	54	66	86	107	78	48
3	51	93	55	59	71	78	75	49	66	102	78	57
4	74	74	54	44	64	82	56	73	69	107	79	52
5	61	84	57	75	63	79	100	69	84	96	80	84
6	62	68	71	54	64	81	73	76	91	83	79	60
7	45	90	66	58	67	83	71	56	108	86	81	66
8	51	95	60	57	70	78	58	53	88	98	76	60
9	75	89	66	72	89	67	71	52	122	91	81	65
10	50	59	66	69	92	102	59	55	109	106	68	62
11	79	78	49	51	94	102	64	54	113	92	92	80
12	39	82	51	50	76	77	83	62	76	82	75	59
13	65	87	67	61	67	96	73	71	97	107	81	65
14	62	61	56	72	62	96	87	52	82	88	73	61
15	57	94	55	65	92	98	42	54	86	94	81	59
16	49	46	66	54	84	78	55	55	87	94	84	77
17	61	69	58	58	80	80	80	72	90	102	79	69
18	67	85	70	59	56	69	58	64	67	112	73	79
19	66	60	50	53	78	95	72	68	115	80	71	47
20	75	97	47	51	80	79	94	85	78	96	73	57
21	69	80	48	66	84	91	77	85	91	92	82	81
22	81	81	65	75	54	63	92	61	78	116	80	64
23	62	68	66	66	70	91	66	74	80	90	82	70
24	80	74	73	64	88	88	82	53	90	114	81	79
25	77	94	49	54	81	90	69	60	79	94	75	61
26	44	49	85	61	89	104	68	75	67	96	75	79
27	87	71	58	58	79	85	82	67	76	124	79	72

28	81	75	51	52	59	100	65	62	87	78	81	73
29	76	56	69	52	46	71	81	75	83	92	82	75
30	76	81	52	53	67	96	73	81	110	79	85	78
31	66	79	72	52	65	94	76	67	95	90	85	71
32	86	76	65	47	60	88	88	55	60	79	79	77
33	60	72	68	48	94	74	89	65	86	96	75	50
34	45	59	59	59	82	79	64	65	106	84	84	70
35	46	63	57	59	81	89	73	58	72	98	75	66
36	55	44	62	50	78	75	86	76	68	105	81	82
37	61	62	49	52	97	100	74	81	85	96	76	57
38	56	70	70	70	88	84	94	87	92	92	70	69
39	67	80	59	55	68	89	81	76	71	112	79	73
40	47	50	62	60	88	79	62	54	93	91	83	76
41	46	71	57	59	89	68	87	80	90	104	79	75
42	69	67	52	47	81	78	62	59	75	98	82	58
43	67	69	45	46	92	102	73	57	67	102	78	69
44	54	52	71	69	89	83	85	66	85	102	75	66
45	78	62	76	56	64	61	93	80	64	134	83	83
46	38	54	76	72	68	100	83	53	88	94	84	73
47	73	71	71	64	62	76	75	58	63	120	80	69
48	74	97	66	58	76	96	77	69	84	96	71	66
49	41	69	42	42	62	93	56	64	74	122	79	70
50	71	54	71	57	48	90	73	49	64	98	83	68
51	73	72	71	53	78	94	52	70	75	94	91	60
52	52	65	64	65	76	75	65	63	85	86	74	70
53	42	70	67	67	55	98	63	60	100	86	78	79
54	38	82	94	77	91	70	76	81	70	96	70	72
55	55	47	69	66	67	78	61	64	95	114	91	76
Mean:	62	72	62	59	75	86	73	65	86	98	79	68
SD:	13.5	14.1	10.2	8.5	13.0	11.3	12.4	9.1	15.1	12.1	5.2	9.4

3- FH/Q Ratio Values of male's participants (post-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT
1	63	70	72	58	66	88	74	45	97	87	81	93
2	70	54	45	59	73	90	47	45	80	87	77	73
3	80	62	33	46	88	107	64	58	103	95	63	57
4	58	56	75	58	63	91	86	70	93	107	86	78
5	74	59	72	61	94	90	85	81	81	118	83	86
6	81	74	39	47	83	90	51	71	92	121	68	76
7	45	94	64	58	54	86	88	76	117	97	72	89
8	75	73	48	38	104	89	82	65	88	101	66	66
9	67	72	43	45	96	90	57	61	97	93	80	75
10	54	91	61	59	94	89	86	71	103	100	102	85
11	54	81	71	43	98	87	89	47	93	121	69	82
12	50	73	44	40	74	89	44	52	103	102	78	67
13	86	73	45	41	91	89	51	52	105	85	94	90
14	60	70	69	59	88	88	86	72	106	102	88	90
15	67	84	48	56	83	88	76	67	111	91	85	83
16	44	85	68	60	63	88	47	60	107	125	104	76
17	68	78	54	54	77	90	81	80	85	107	72	65
18	83	85	76	62	87	89	86	68	122	91	93	82
19	85	66	45	58	103	86	68	76	87	96	90	73
20	67	91	61	61	69	88	68	73	100	90	63	53
21	78	75	71	44	100	88	69	41	86	97	93	91
22	63	78	63	58	68	87	83	58	75	91	87	76
23	61	68	63	57	64	91	59	78	69	87	96	64
24	76	79	59	52	90	87	76	72	100	80	89	77
25	61	70	38	51	77	88	51	50	86	113	104	83
26	71	68	76	52	95	88	81	64	92	111	70	66
27	67	68	76	55	108	87	85	58	88	92	86	82

28	56	64	70	46	63	72	86	57	89	111	89	90
29	48	81	64	53	86	101	50	78	103	96	100	70
30	61	90	73	52	70	89	83	68	83	100	84	88
31	70	61	78	46	79	89	81	55	97	88	86	88
32	80	67	59	50	82	86	46	54	94	79	71	56
33	58	65	49	51	76	89	60	56	67	107	102	88
34	55	61	49	44	87	89	66	67	106	97	65	73
35	73	65	42	45	104	90	62	48	90	133	97	78
36	57	87	56	53	59	75	53	48	83	102	89	75
37	65	88	68	52	77	100	87	66	115	88	76	61
38	69	69	55	44	88	76	63	74	85	103	66	69
39	57	75	65	46	89	98	78	47	73	101	72	69
40	53	69	58	45	78	87	83	58	115	91	69	70
41	54	74	46	50	80	110	78	70	100	127	83	87
42	63	96	47	52	96	89	66	75	83	134	97	89
43	74	60	43	53	111	89	77	58	95	93	80	65
44	79	79	48	44	91	86	67	62	74	103	87	74
45	85	59	73	45	67	88	72	43	98	106	61	55
46	46	71	79	47	58	88	78	66	92	89	86	79
47	49	89	73	55	55	52	76	74	85	85	79	83
48	64	73	70	54	72	88	62	39	100	104	91	57
49	67	69	58	56	86	55	52	67	83	90	96	90
50	68	88	56	54	89	103	69	71	100	85	90	87
Mean:	65	74	59	51	82	88	70	62	94	100	83	76
SD:	11.3	10.6	12.6	6.2	14.4	9.6	13.7	11.3	12.4	13.3	11.9	11.0

4- FH/Q Ratio Values of female's participants (post-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT	FR-PT at15°	FR-PT at30°	FR-PT at45°	FR-of PT
1	43	47	47	36	82	91	28	40	74	100	85	53
2	37	53	44	40	68	89	42	31	83	93	43	48
3	43	60	49	31	62	96	44	35	80	85	81	70
4	49	49	27	40	55	95	32	45	117	83	61	81
5	58	46	31	41	68	78	42	72	107	97	65	63
6	41	54	50	35	54	66	51	43	67	96	87	56
7	51	60	41	42	79	83	67	54	82	92	49	45
8	38	58	38	39	71	78	54	47	108	95	52	57
9	59	47	33	44	74	91	47	41	83	100	74	55
10	58	45	43	37	78	62	64	58	66	105	55	40
11	39	42	28	24	74	83	40	41	68	91	61	51
12	43	53	51	28	53	69	67	42	61	102	74	53
13	42	50	49	28	67	59	73	65	90	100	67	72
14	42	52	41	39	72	84	64	62	62	81	47	48
15	38	70	50	40	64	77	42	38	81	93	54	46
16	34	67	47	34	59	87	41	44	79	73	55	56
17	32	59	52	40	55	100	59	37	91	90	70	65
18	59	55	37	44	74	100	73	37	96	98	66	53
19	38	46	44	43	45	104	70	40	91	115	51	48
20	43	50	52	30	81	56	63	36	84	79	88	66
21	51	49	32	36	52	81	30	40	108	112	87	61
22	46	54	38	46	56	46	74	69	82	85	90	57
23	36	48	42	46	56	86	64	47	83	86	40	47
24	42	38	43	44	87	100	64	45	59	83	68	29
25	44	63	51	31	80	69	48	57	85	118	56	42
26	56	55	54	22	84	109	67	33	104	85	56	62
27	50	74	35	46	68	77	50	45	83	88	81	68

28	47	51	33	52	68	95	41	43	88	96	48	65
29	58	55	41	40	77	105	71	53	55	76	56	60
30	63	80	54	32	65	62	58	48	86	95	60	55
31	43	51	45	37	67	63	54	45	111	80	69	57
32	45	64	50	34	61	89	65	42	72	100	50	49
33	56	63	34	23	82	49	55	51	93	89	87	58
34	39	67	42	33	51	95	45	54	65	96	72	64
35	63	59	27	37	66	75	12	34	74	98	61	46
36	53	52	28	40	64	95	57	28	74	80	78	78
37	41	50	30	39	74	84	50	57	96	105	64	68
38	49	55	49	32	79	100	58	65	93	93	71	59
39	55	64	49	34	67	83	59	72	109	89	74	53
40	43	70	26	36	50	54	42	32	88	100	68	72
41	25	79	27	31	66	76	57	45	89	120	89	69
42	43	52	27	29	67	92	41	68	61	120	67	60
43	50	52	35	33	68	71	43	40	77	88	78	47
44	38	64	34	22	73	69	51	42	68	85	74	66
45	54	77	48	40	61	100	50	43	117	88	74	52
46	56	55	40	38	60	97	37	64	67	100	62	36
47	42	59	53	39	64	89	62	39	117	90	54	62
48	58	75	38	33	67	58	44	38	71	95	66	68
49	43	61	58	42	75	76	48	40	76	77	63	69
50	47	47	49	30	81	89	52	70	53	91	63	71
Mean:	46	57	41	36	67	81	52	47	82	94	66	58
SD:	8.5	9.8	8.9	6.6	10.0	15.8	13.1	11.7	16.8	11.0	13.0	10.7

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Appendix (7)

EMD values of male's participants and females (pre-post fatigue)

1- EMD Values of male's participants (pre-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX
1	27	20	27	27	36	32	18	36	60	55	66	66
2	25	29	24	29	28	32	43	43	51	55	54	55
3	28	29	30	30	39	37	29	39	49	47	40	49
4	25	24	24	25	54	63	66	66	58	64	61	64
5	21	25	21	25	34	37	27	37	47	55	52	55
6	19	18	18	19	56	40	53	56	53	64	47	64
7	28	24	19	28	43	40	41	43	43	36	51	51
8	24	23	32	32	25	46	33	46	59	46	63	63
9	22	22	25	25	39	43	20	43	60	46	56	60
10	25	22	18	25	22	32	22	32	58	62	55	62
11	23	24	26	26	39	25	32	39	41	48	58	58
12	24	22	20	24	48	28	47	48	50	44	60	60
13	20	26	23	26	37	25	44	44	43	59	66	66
14	31	21	25	31	27	21	26	27	45	44	64	64
15	25	23	24	25	34	56	59	59	46	62	46	62
16	24	30	31	31	35	30	48	48	39	52	47	52
17	21	25	21	25	33	28	42	42	48	33	31	48
18	21	20	19	21	61	42	56	61	52	65	48	65
19	22	23	25	25	45	30	48	48	52	35	44	52
20	27	27	29	29	39	34	25	39	58	54	67	67
21	25	20	25	25	63	64	35	64	67	64	55	67
22	27	25	28	28	41	38	37	41	53	60	50	60
23	28	24	25	28	39	33	31	39	48	47	39	48
24	19	24	25	25	20	21	26	26	60	59	51	60
25	22	24	27	27	52	55	68	68	57	56	39	57
26	20	19	25	25	27	32	17	32	70	64	66	70
27	26	30	23	30	45	54	64	64	53	59	47	59

28	27	22	27	27	35	21	19	35	67	71	67	71
29	19	23	25	25	27	50	38	50	57	70	51	70
30	26	19	21	26	62	56	49	62	46	59	61	61
31	27	30	21	30	21	33	20	33	48	46	50	50
32	28	27	26	28	40	34	45	45	54	61	62	62
33	24	19	20	24	38	30	24	38	39	40	43	43
34	22	21	21	22	32	21	24	32	41	44	48	48
35	24	30	27	30	57	57	58	58	42	43	49	49
36	26	30	21	30	58	57	38	58	41	45	57	57
37	23	24	32	32	61	37	68	68	67	68	53	68
38	20	23	19	23	36	51	44	51	52	34	49	52
39	21	30	24	30	57	50	58	58	57	42	59	59
40	25	19	18	25	24	39	45	45	52	44	37	52
41	21	26	27	27	39	40	57	57	66	70	66	70
42	18	25	23	25	23	25	28	28	45	44	52	52
43	22	25	24	25	40	48	46	48	46	42	62	62
44	27	21	22	27	48	32	40	48	52	62	64	64
45	24	31	31	31	43	47	29	47	49	35	38	49
46	29	27	33	33	47	38	56	56	56	65	67	67
47	25	27	30	30	23	40	20	40	54	61	51	61
48	25	29	30	30	37	55	57	57	57	41	36	57
49	27	28	27	28	25	36	36	36	31	34	45	45
50	26	30	23	30	40	47	40	47	67	52	63	67
51	24	22	27	27	59	60	63	63	57	62	66	66
52	30	23	23	30	23	37	32	37	52	66	63	66
53	25	28	23	28	37	27	29	37	61	48	49	61
54	19	20	21	21	54	59	40	59	42	61	40	61
55	30	27	33	33	36	29	44	44	64	49	55	64
Mean:	24	25	25	27	40	40	40	47	52	53	53	59
SD:	3.2	3.6	4.0	3.1	12.0	11.9	14.4	11.2	8.5	10.8	9.6	7.2

2- EMD Values of female's participants (pre-fatigue)

No.	Slow angular velocity ($60°·s^{-1}$)				Intermediate angular velocity ($120°·s^{-1}$)				Fast angular velocity ($240°·s^{-1}$)			
	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX
1	31	26	26	31	64	64	53	64	47	68	58	68
2	27	27	16	27	53	34	30	53	54	66	57	66
3	33	35	25	35	36	21	19	36	68	66	58	68
4	32	32	29	32	37	53	39	53	55	68	66	68
5	22	24	18	24	44	25	29	44	42	46	55	55
6	29	21	27	29	41	34	37	41	52	53	54	54
7	32	27	34	34	41	35	45	45	62	52	62	62
8	30	21	29	30	26	26	31	31	70	69	62	70
9	28	22	23	28	62	66	40	66	57	70	63	70
10	22	26	24	26	47	40	26	47	50	64	47	64
11	27	24	20	27	37	34	26	37	56	60	55	60
12	28	26	31	31	39	38	60	60	42	48	44	48
13	27	24	25	27	45	42	47	47	66	71	48	71
14	27	26	26	27	65	67	69	69	64	48	52	64
15	20	21	24	24	23	28	18	28	63	64	65	65
16	20	29	23	29	48	48	47	48	53	71	57	71
17	31	29	34	34	55	59	59	59	63	60	61	63
18	22	20	22	22	28	54	37	54	48	34	43	48
19	22	29	25	29	30	23	39	39	57	50	65	65
20	23	22	22	23	25	44	36	44	67	55	60	67
21	30	29	32	32	43	58	33	58	73	67	66	73
22	23	24	18	24	25	49	44	49	65	58	61	65
23	20	21	22	22	63	49	54	63	58	47	37	58
24	21	22	28	28	57	50	44	57	54	51	46	54
25	30	26	27	30	69	41	47	69	74	60	55	74
26	19	28	24	28	47	35	38	47	39	54	42	54
27	20	22	22	22	39	51	36	51	51	57	54	57

28	28	29	23	29	59	46	38	59	46	64	64	64
29	31	22	25	31	56	38	45	56	48	59	53	59
30	31	28	32	32	64	69	47	69	56	62	53	62
31	28	23	33	33	25	47	34	47	70	55	51	70
32	28	25	26	28	36	42	37	42	59	56	42	59
33	31	32	28	32	41	45	65	65	65	71	71	71
34	23	24	23	24	32	32	44	44	47	50	60	60
35	24	21	19	24	30	22	35	35	56	56	47	56
36	32	34	27	34	33	22	27	33	70	50	61	70
37	24	29	31	31	25	25	36	36	57	51	64	64
38	27	31	32	32	39	45	50	50	44	37	39	44
39	27	25	22	27	34	40	50	50	56	46	54	56
40	29	24	29	29	48	58	67	67	69	70	64	70
41	24	30	27	30	52	67	64	67	50	54	64	64
42	25	28	26	28	39	35	45	45	49	61	59	61
43	30	28	34	34	50	41	60	60	52	58	60	60
44	31	30	30	31	53	39	58	58	60	42	62	62
45	22	24	21	24	22	36	29	36	41	60	62	62
46	32	31	30	32	53	59	46	59	65	62	63	65
47	31	31	31	31	48	48	43	48	63	61	51	63
48	27	31	32	32	45	38	56	56	58	66	64	66
49	28	33	34	34	48	47	37	48	55	47	68	68
50	34	34	29	34	23	21	52	52	51	50	48	51
51	27	22	23	27	45	50	40	50	64	67	59	67
52	29	25	30	30	39	41	35	41	64	60	78	78
53	23	31	27	31	26	35	55	55	73	69	64	73
54	20	27	29	29	61	37	43	61	60	71	56	71
55	25	28	28	28	20	33	26	33	32	37	41	41
Mean:	27	27	26	29	42	42	43	51	57	58	57	63
SD:	4.1	3.9	4.5	3.5	13.1	12.6	12.0	10.8	9.5	9.5	8.6	7.7

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3- EMD Values of male's participants (post-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX
1	27	25	21	27	70	59	63	70	83	54	69	83
2	19	25	36	36	53	45	44	53	92	86	80	92
3	30	30	22	30	65	64	76	76	65	72	74	74
4	45	56	59	59	45	38	41	45	89	77	82	89
5	25	30	20	30	57	76	67	76	59	48	59	59
6	47	33	46	47	46	35	40	46	70	61	67	70
7	34	33	34	34	53	63	54	63	86	88	81	88
8	27	39	26	39	59	54	77	77	81	78	71	81
9	30	36	23	36	48	36	61	61	80	81	87	87
10	24	25	19	25	62	62	72	72	72	71	69	72
11	30	22	25	30	37	37	39	39	62	77	58	77
12	39	21	40	40	48	52	42	52	73	74	92	92
13	28	21	37	37	66	67	60	67	47	52	71	71
14	23	24	19	24	55	55	48	55	81	76	66	81
15	25	49	52	52	48	50	50	50	64	72	73	73
16	26	23	41	41	35	50	41	50	84	76	94	94
17	24	21	35	35	53	55	69	69	98	84	94	98
18	52	35	49	52	33	44	30	44	68	65	77	77
19	36	23	41	41	40	47	32	47	62	53	70	70
20	30	27	18	30	69	58	58	69	87	93	82	93
21	54	57	28	57	63	74	64	74	72	77	66	77
22	32	31	30	32	53	64	56	64	69	81	62	81
23	30	26	24	30	27	27	36	36	69	70	51	70
24	23	24	19	24	35	48	37	48	72	70	79	79
25	43	48	61	61	32	54	39	54	83	80	83	83
26	23	25	20	25	55	41	46	55	76	86	86	86
27	36	47	57	57	53	64	53	64	65	74	62	74

28	26	24	20	26	69	47	73	73	81	86	85	86
29	21	43	31	43	75	70	64	75	69	93	88	93
30	53	49	42	53	49	56	66	66	92	71	86	92
31	23	26	19	26	48	40	36	48	79	89	84	89
32	31	27	38	38	39	26	30	39	54	46	63	63
33	29	23	17	29	53	46	38	53	84	68	82	84
34	23	23	17	23	29	32	44	44	55	55	74	74
35	48	50	51	51	31	36	46	46	74	59	67	74
36	49	50	30	50	47	37	48	48	74	71	60	74
37	52	30	60	60	55	57	61	61	58	71	55	71
38	27	44	36	44	45	40	59	59	63	70	68	70
39	48	43	50	50	67	58	72	72	76	77	71	77
40	29	32	37	37	55	65	52	65	75	92	85	92
41	30	33	49	49	47	64	46	64	75	71	56	75
42	25	21	20	25	62	53	51	62	78	79	71	79
43	31	41	38	41	77	64	60	77	72	79	96	96
44	39	25	32	39	67	49	62	67	78	86	69	86
45	34	40	21	40	73	59	65	73	63	93	68	93
46	38	31	48	48	42	48	32	48	75	65	75	75
47	26	33	23	33	55	60	49	60	84	84	74	84
48	28	48	49	49	58	73	73	73	74	81	74	81
49	26	29	28	29	51	38	46	51	75	70	86	86
50	31	40	32	40	43	55	43	55	65	85	60	85
Mean:	33	33	34	39	52	52	52	59	74	74	74	81
SD:	9.5	10.4	13.0	10.9	12.5	12.3	13.2	11.6	10.6	11.8	11.1	9.0

4- EMD Values of male's participants (pre-fatigue)

No.	Slow angular velocity (60°·s^{-1})				Intermediate angular velocity (120°·s^{-1})				Fast angular velocity (240°·s^{-1})			
	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX	EMD BM	EMD SM	EMD ST	EMD MAX
1	60	61	65	65	73	77	82	82	64	90	74	90
2	24	38	34	38	68	65	78	78	91	99	97	99
3	38	28	31	38	69	92	80	92	91	91	97	97
4	55	60	42	60	50	51	55	55	92	63	80	92
5	37	30	46	46	78	78	62	78	81	81	78	81
6	65	65	55	65	49	50	52	52	80	79	83	83
7	54	35	32	54	39	56	49	56	98	86	83	98
8	37	22	21	37	76	72	68	76	68	84	80	84
9	38	54	41	54	52	53	56	56	86	78	90	90
10	45	26	31	45	70	63	63	70	92	90	79	92
11	42	35	39	42	76	64	59	76	93	86	94	94
12	42	36	47	47	75	69	63	75	91	95	90	95
13	27	27	33	33	55	54	53	55	92	68	90	92
14	63	67	42	67	63	79	67	79	87	82	96	96
15	48	41	28	48	50	59	61	61	72	78	71	78
16	38	35	28	38	80	66	66	80	82	73	77	82
17	40	39	62	62	52	58	50	58	83	84	93	93
18	46	43	49	49	49	52	44	52	86	90	94	94
19	66	68	71	71	64	43	48	64	83	70	92	92
20	24	29	20	29	54	50	67	67	78	68	79	79
21	49	49	49	49	75	63	86	86	83	72	96	96
22	56	60	61	61	65	50	74	74	73	76	70	76
23	29	55	39	55	45	42	61	61	86	91	85	91
24	31	24	41	41	44	53	46	53	66	94	88	94
25	26	45	38	45	84	76	67	84	79	89	64	89
26	44	59	35	59	62	69	75	75	64	82	78	82
27	26	50	46	50	51	51	54	54	72	92	88	92

28	64	50	56	64	85	79	66	85	97	89	87	97
29	58	51	46	58	77	78	53	78	98	87	88	98
30	70	42	48	70	73	55	76	76	91	90	83	91
31	48	36	39	48	52	38	48	52	89	97	96	97
32	40	52	37	52	71	62	59	71	91	81	93	93
33	60	47	39	60	77	85	76	85	95	72	86	95
34	57	39	46	57	68	90	80	90	95	93	78	95
35	65	70	48	70	46	68	68	68	97	97	98	98
36	26	48	35	48	55	56	74	74	81	93	98	98
37	37	43	38	43	38	40	51	51	82	93	86	93
38	42	46	66	66	53	42	46	53	99	89	94	99
39	33	33	45	45	44	60	65	65	95	89	88	95
40	31	23	36	36	62	89	88	89	84	93	96	96
41	34	23	28	34	38	45	51	51	88	78	87	88
42	26	26	37	37	56	78	59	78	66	64	66	66
43	40	46	51	51	48	37	51	51	65	72	71	72
44	35	41	51	51	67	64	56	67	88	68	84	88
45	49	59	68	68	85	90	82	90	84	85	86	86
46	53	68	65	68	54	57	48	57	86	91	70	91
47	40	36	46	46	49	63	63	63	79	87	70	87
48	51	42	61	61	53	64	50	64	92	80	77	92
49	54	40	59	59	79	81	73	81	89	83	77	89
50	23	37	30	37	56	78	77	78	81	96	97	97
Mean:	44	44	44	52	61	63	63	69	85	84	85	90
SD:	13.1	13.3	12.4	11.4	13.4	14.7	12.0	12.7	9.7	9.4	9.3	7.3

Appendix (8)

Examples of Statistical Analysis:

1- Tests of Within-Subjects Effects for FH/Q ratio

Measure:MEASURE_1						
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	74841.303	1.000	74841.303	672.431	0.000
	Greenhouse-Geisser	74841.303	1.000	74841.303	672.431	0.000
	Huynh-Feldt	74841.303	1.000	74841.303	672.431	0.000
	Lower-bound	74841.303	1.000	74841.303	672.431	0.000
time * SEX	Sphericity Assumed	1621.584	1.000	1621.584	14.570	0.000
	Greenhouse-Geisser	1621.584	1.000	1621.584	14.570	0.000
	Huynh-Feldt	1621.584	1.000	1621.584	14.570	0.000
	Lower-bound	1621.584	1.000	1621.584	14.570	0.000
Error(time)	Sphericity Assumed	10907.365	98.000	111.300		
	Greenhouse-Geisser	10907.365	98.000	111.300		
	Huynh-Feldt	10907.365	98.000	111.300		
	Lower-bound	10907.365	98.000	111.300		
velocity	Sphericity Assumed	252825.574	2.000	126412.787	974.729	0.000
	Greenhouse-Geisser	252825.574	1.941	130273.150	974.729	0.000
	Huynh-Feldt	252825.574	2.000	126442.469	974.729	0.000
	Lower-bound	252825.574	1.000	252825.574	974.729	0.000
velocity * SEX	Sphericity Assumed	1439.872	2.000	719.936	5.551	0.005
	Greenhouse-Geisser	1439.872	1.941	741.921	5.551	0.005
	Huynh-Feldt	1439.872	2.000	720.105	5.551	0.005
	Lower-bound	1439.872	1.000	1439.872	5.551	0.020
Error(velocity)	Sphericity Assumed	25419.283	196.000	129.690		
	Greenhouse-Geisser	25419.283	190.192	133.651		
	Huynh-Feldt	25419.283	195.954	129.721		
	Lower-bound	25419.283	98.000	259.380		
angles	Sphericity Assumed	188321.383	3.000	62773.794	468.466	0.000

	Greenhouse-Geisser	188321.383	2.457	76639.574	468.466	0.000
	Huynh-Feldt	188321.383	2.551	73824.443	468.466	0.000
	Lower-bound	188321.383	1.000	188321.383	468.466	0.000
angles * SEX	Sphericity Assumed	2392.602	3.000	797.534	5.952	0.001
	Greenhouse-Geisser	2392.602	2.457	973.697	5.952	0.001
	Huynh-Feldt	2392.602	2.551	937.931	5.952	0.001
	Lower-bound	2392.602	1.000	2392.602	5.952	0.016
Error(angles)	Sphericity Assumed	39395.560	294.000	133.999		
	Greenhouse-Geisser	39395.560	240.809	163.597		
	Huynh-Feldt	39395.560	249.992	157.587		
	Lower-bound	39395.560	98.000	401.996		
time * velocity	Sphericity Assumed	3440.494	2.000	1720.247	10.260	0.000
	Greenhouse-Geisser	3440.494	1.769	1944.349	10.260	0.000
	Huynh-Feldt	3440.494	1.818	1892.447	10.260	0.000
	Lower-bound	3440.494	1.000	3440.494	10.260	0.002
time * velocity * SEX	Sphericity Assumed	3336.501	2.000	1668.251	9.950	0.000
	Greenhouse-Geisser	3336.501	1.769	1885.580	9.950	0.000
	Huynh-Feldt	3336.501	1.818	1835.246	9.950	0.000
	Lower-bound	3336.501	1.000	3336.501	9.950	0.002
Error(time*velocity)	Sphericity Assumed	32861.785	196.000	167.662		
	Greenhouse-Geisser	32861.785	173.409	189.504		
	Huynh-Feldt	32861.785	178.165	184.446		
	Lower-bound	32861.785	98.000	335.324		
time * angles	Sphericity Assumed	6081.674	3.000	2027.225	15.451	0.000
	Greenhouse-Geisser	6081.674	2.637	2306.021	15.451	0.000
	Huynh-Feldt	6081.674	2.745	2215.888	15.451	0.000
	Lower-bound	6081.674	1.000	6081.674	15.451	0.000
time * angles * SEX	Sphericity Assumed	1413.207	3.000	471.069	3.590	0.014
	Greenhouse-Geisser	1413.207	2.637	535.853	3.590	0.018
	Huynh-Feldt	1413.207	2.745	514.909	3.590	0.017
	Lower-bound	1413.207	1.000	1413.207	3.590	0.061
Error(time*angles)	Sphericity Assumed	38573.172	294.000	131.201		
	Greenhouse-Geisser	38573.172	258.456	149.245		
	Huynh-Feldt	38573.172	268.968	143.412		

	Lower-bound	38573.172	98.000	393.604		
velocity * angles	Sphericity Assumed	6976.809	6.000	1162.801	9.988	0.000
	Greenhouse-Geisser	6976.809	5.059	1379.007	9.988	0.000
	Huynh-Feldt	6976.809	5.422	1286.745	9.988	0.000
	Lower-bound	6976.809	1.000	6976.809	9.988	0.002
velocity * angles * SEX	Sphericity Assumed	2007.057	6.000	334.509	2.873	0.009
	Greenhouse-Geisser	2007.057	5.059	396.706	2.873	0.014
	Huynh-Feldt	2007.057	5.422	370.165	2.873	0.012
	Lower-bound	2007.057	1.000	2007.057	2.873	0.093
Error(velocity*angles)	Sphericity Assumed	68453.288	588.000	116.417		
	Greenhouse-Geisser	68453.288	495.811	138.063		
	Huynh-Feldt	68453.288	531.362	128.826		
	Lower-bound	68453.288	98.000	698.503		
time * velocity * angles	Sphericity Assumed	1270.046	6.000	211.674	1.633	0.135
	Greenhouse-Geisser	1270.046	4.726	268.750	1.633	0.154
	Huynh-Feldt	1270.046	5.045	251.740	1.633	0.149
	Lower-bound	1270.046	1.000	1270.046	1.633	0.204
time * velocity * angles * SEX	Sphericity Assumed	1157.899	6.000	192.983	1.489	0.179
	Greenhouse-Geisser	1157.899	4.726	245.019	1.489	0.195
	Huynh-Feldt	1157.899	5.045	229.511	1.489	0.191
	Lower-bound	1157.899	1.000	1157.899	1.489	0.225
Error(time*velocity*angles)	Sphericity Assumed	76202.825	588.000	129.597		
	Greenhouse-Geisser	76202.825	463.123	164.541		
	Huynh-Feldt	76202.825	494.416	154.127		
	Lower-bound	76202.825	98.000	777.580		

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2- Tests of Within-Subjects Effects for EMD

Measure:MEASURE_1						
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	143433.680	1.000	143433.680	709.406	0.000
	Greenhouse-Geisser	143433.680	1.000	143433.680	709.406	0.000
	Huynh-Feldt	143433.680	1.000	143433.680	709.406	0.000
	Lower-bound	143433.680	1.000	143433.680	709.406	0.000
time * SEX	Sphericity Assumed	5810.420	1.000	5810.420	28.738	0.000
	Greenhouse-Geisser	5810.420	1.000	5810.420	28.738	0.000
	Huynh-Feldt	5810.420	1.000	5810.420	28.738	0.000
	Lower-bound	5810.420	1.000	5810.420	28.738	0.000
Error(time)	Sphericity Assumed	19814.456	98.000	202.188		
	Greenhouse-Geisser	19814.456	98.000	202.188		
	Huynh-Feldt	19814.456	98.000	202.188		
	Lower-bound	19814.456	98.000	202.188		
velocity	Sphericity Assumed	365714.364	2.000	182857.182	1028.341	0.000
	Greenhouse-Geisser	365714.364	1.926	189890.551	1028.341	0.000
	Huynh-Feldt	365714.364	1.984	184350.004	1028.341	0.000
	Lower-bound	365714.364	1.000	365714.364	1028.341	0.000
velocity * SEX	Sphericity Assumed	76.493	2.000	38.247	0.215	0.807
	Greenhouse-Geisser	76.493	1.926	39.718	0.215	0.798
	Huynh-Feldt	76.493	1.984	38.559	0.215	0.805
	Lower-bound	76.493	1.000	76.493	0.215	0.644
Error(velocity)	Sphericity Assumed	34852.253	196.000	177.818		
	Greenhouse-Geisser	34852.253	188.740	184.657		
	Huynh-Feldt	34852.253	194.413	179.269		
	Lower-bound	34852.253	98.000	355.635		
muscles	Sphericity Assumed	63.054	3.000	31.527	0.468	0.627

	Greenhouse-Geisser	63.054	2.994	31.622	0.468	0.626
	Huynh-Feldt	63.054	2.000	31.527	0.468	0.627
	Lower-bound	63.054	1.000	63.054	0.468	0.495
muscles * SEX	Sphericity Assumed	11.290	3.000	5.645	0.084	0.920
	Greenhouse-Geisser	11.290	1.994	5.662	0.084	0.919
	Huynh-Feldt	11.290	2.000	5.645	0.084	0.920
	Lower-bound	11.290	1.000	11.290	0.084	0.773
Error(muscles)	Sphericity Assumed	13193.433	196.000	67.313		
	Greenhouse-Geisser	13193.433	195.413	67.516		
	Huynh-Feldt	13193.433	196.000	67.313		
	Lower-bound	13193.433	98.000	134.627		
time * velocity	Sphericity Assumed	10934.560	2.000	5467.280	20.459	0.000
	Greenhouse-Geisser	10934.560	1.764	6200.199	20.459	0.000
	Huynh-Feldt	10934.560	1.812	6035.293	20.459	0.000
	Lower-bound	10934.560	1.000	10934.560	20.459	0.000
time * velocity * SEX	Sphericity Assumed	100.253	2.000	50.127	0.188	0.829
	Greenhouse-Geisser	100.253	1.764	56.846	0.188	0.802
	Huynh-Feldt	100.253	1.812	55.334	0.188	0.808
	Lower-bound	100.253	1.000	100.253	0.188	0.666
Error(time*velocity)	Sphericity Assumed	52377.631	196.000	267.233		
	Greenhouse-Geisser	52377.631	172.831	303.057		
	Huynh-Feldt	52377.631	177.553	294.996		
	Lower-bound	52377.631	98.000	534.466		
time * muscles	Sphericity Assumed	23.243	3.000	11.622	0.259	0.772
	Greenhouse-Geisser	23.243	2.961	11.854	0.259	0.767
	Huynh-Feldt	23.243	2.000	11.622	0.259	0.772
	Lower-bound	23.243	1.000	23.243	0.259	0.612
time * muscles * SEX	Sphericity Assumed	26.763	3.000	13.382	0.299	0.742
	Greenhouse-Geisser	26.763	2.961	13.649	0.299	0.738
	Huynh-Feldt	26.763	2.000	13.382	0.299	0.742
	Lower-bound	26.763	1.000	26.763	0.299	0.586

Error(time*muscles)	Sphericity Assumed	8781.104	196.000	44.802		
	Greenhouse-Geisser	8781.104	192.160	45.697		
	Huynh-Feldt	8781.104	196.000	44.802		
	Lower-bound	8781.104	98.000	89.603		
velocity * muscles	Sphericity Assumed	6.539	6.000	1.635	0.035	0.998
	Greenhouse-Geisser	6.539	5.645	1.794	0.035	0.996
	Huynh-Feldt	6.539	4.842	1.702	0.035	0.997
	Lower-bound	6.539	1.000	6.539	0.035	0.853
velocity * muscles * SEX	Sphericity Assumed	52.997	6.000	13.249	0.280	0.891
	Greenhouse-Geisser	52.997	4.645	14.538	0.280	0.875
	Huynh-Feldt	52.997	3.842	13.793	0.280	0.884
	Lower-bound	52.997	1.000	52.997	0.280	0.598
Error(velocity*muscles)	Sphericity Assumed	18530.020	392.000	47.270		
	Greenhouse-Geisser	18530.020	357.254	51.868		
	Huynh-Feldt	18530.020	376.552	49.210		
	Lower-bound	18530.020	98.000	189.082		
time * velocity * muscles	Sphericity Assumed	32.317	6.000	8.079	0.134	0.970
	Greenhouse-Geisser	32.317	4.265	9.897	0.134	0.950
	Huynh-Feldt	32.317	3.426	9.433	0.134	0.955
	Lower-bound	32.317	1.000	32.317	0.134	0.715
time * velocity * muscles * SEX	Sphericity Assumed	66.183	4.000	16.546	0.275	0.894
	Greenhouse-Geisser	66.183	5.265	20.268	0.275	0.859
	Huynh-Feldt	66.183	3.426	19.319	0.275	0.868
	Lower-bound	66.183	1.000	66.183	0.275	0.601
Error(time*velocity*muscles)	Sphericity Assumed	23582.389	392.000	60.159		
	Greenhouse-Geisser	23582.389	320.007	73.693		
	Huynh-Feldt	23582.389	335.724	70.243		
	Lower-bound	23582.389	98.000	240.637		