

**The University of Hull**

**Effect of Fatigue on Hamstring Strain Injury Risk in Soccer**

**Being a Thesis submitted for the Degree of Doctor of Philosophy**

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**by**

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## List of Abbreviations, Acronyms and Symbols

|                     |   |
|---------------------|---|
| ACL                 | anterior cruciate ligament                        |
| APT                 | angle of peak torque                              |
| ASIS                | anterior superior iliac spine                     |
| ATFL                | anterior talofibular ligament                     |
| b·min <sup>-1</sup> | beats per minute                                  |
| CD                  | cool-down   |
| conH                | concentric hamstrings                             |
| conQ                | concentric quadriceps                             |
| conH:conQ           | concentric hamstrings:concentric quadriceps ratio |
| eccH                | eccentric hamstrings                              |
| eccH:conQ           | eccentric hamstrings:concentric quadriceps ratio  |
| EMD                 | electromechanical delay                           |
| EMG                 | electromyography                                  |
| F                   | Fahrenheit  |
| FA                  | Football Association                              |
| FIFA                | Fédération International de Football Association  |
| HR                  | heart rate  |
| H:Q                 | hamstring:quadriceps ratio                        |
| hr                  | hour  |
| Hz                  | hertz   |
| ICC                 | intra-class correlation coefficient               |

|                      |   |
|----------------------|---|
| km                   | kilometres  |
| kg                   | kilograms   |
| L                    | lumbar spine                                      |
| LIST                 | Loughborough Intermittent Shuttle Test            |
| M                    | mean  |
| m                    | meters  |
| MCL                  | medial collateral ligament                        |
| min                  | minutes   |
| ml                   | millilitres                                       |
| mm                   | millimetres                                       |
| mmol·L <sup>-1</sup> | millimoles per litre                              |
| ms                   | milliseconds                                      |
| m·s <sup>-1</sup>    | meters per second                                 |
| n                    | number of subjects in sample                      |
| N·m                  | newton meters                                     |
| PHISR                | prolonged intermittent high intensity shuttle run |
| PSIS                 | posterior superior iliac spine                    |
| PT                   | peak torque                                       |
| <i>r</i>             | Pearson's correlation coefficient                 |
| rad                  | radians   |

|                    |  |
|--------------------|--|
| s                  | seconds  |
| SAFT <sup>90</sup> | 90 min soccer-specific aerobic field test      |
| SD                 | standard deviation                             |
| SSEP               | sport-specific intermittent treadmill protocol |
| TFD                | tibio-femoral displacement                     |
| $t_x$              | time $x$ minutes                               |
| USD                | united states dollars                          |
| VCM                | velocity centre of mass                        |
| $\dot{V}O_2$       | oxygen uptake                                  |
| $\dot{V}O_{2\max}$ | maximal oxygen uptake                          |
| vs                 | versus   |
| WU                 | warm-up  |
| yrs                | years  |
| °                  | degrees  |
| °C                 | degrees celcius                                |

## Abstract

Hamstring strains are one of the primary injuries within modern soccer match-play. The injury is well recognised by medical personnel, coaches and athletes as a major concern causing significant financial costs and lost time from training and matches. The temporal pattern of hamstring injury incidence during matches has shown almost half of all injuries to occur during the latter stages of each half, thus suggesting fatigue as an important contributing factor for injury. This thesis comprises four experimental chapters that examine the effect of multidirectional soccer-specific fatigue on the primary aetiological risk factors and mechanism of injury. This was then used to create and evaluate an injury prevention programme aimed at reducing the risk of hamstring strains in soccer.

In the first experimental chapter, a multidirectional soccer-specific free-running match simulation (SAFT<sup>90</sup>) was developed based on the activity profile of modern soccer match-play (Prozone<sup>®</sup>). The simulation was evaluated by assessing players' physiological responses of heart rate, core body temperature, fluid loss and blood lactate, and sprinting performance. Findings showed that the SAFT<sup>90</sup> induced similar physiological responses, such as cardiovascular strain, thermal strain, blood lactate accumulation and dehydration as has been observed during actual matches. The SAFT<sup>90</sup> also caused a reduction in sprint performance by 7% of maximal performance as a function of time, also comparable with match-play observations. The decrement in sprint performance with fatigue may be related to the temporal pattern of increased incidence of hamstring injuries reported during the latter stages of soccer match-play. It was therefore hypothesised that altered sprinting technique or muscle function under fatigued conditions associated with soccer match-play may contribute to increased susceptibility to hamstring injury.

The second experimental chapter investigated the effects of the SAFT<sup>90</sup> on changes in sprinting kinematics related to hamstring injury risk. Results supported findings from the previous chapter with a time dependant impairment in sprint performance by 8% during the exercise protocol and corresponding with a 17% reduction in stride length over the 90 min. During fatigued sprinting at the ends of each half of the SAFT<sup>90</sup>, a significant reduction in hamstring flexibility during the late swing phase of the gait cycle was observed ( $P < 0.05$ ). Contrastingly, there was a significant increase in rectus femoris flexibility indicated earlier in the gait cycle with fatigue ( $P < 0.05$ ) and

consequently a significant increase in lower limb segmental velocity at the ends of each half of the SAFT<sup>90</sup> ( $P < 0.05$ ). These findings suggested increased strain on the hamstrings and therefore increased risk of injury during the final stages of simulated soccer match-play.

The third experimental chapter examined the effect of the SAFT<sup>90</sup> on the eccentric hamstring strength and hamstring:quadriceps muscular imbalances, given their previous association within the literature as risk factors for hamstring strains. Isokinetic concentric hamstrings and quadriceps peak torque was maintained during the match simulation showing no significant changes over the 90 min ( $P > 0.05$ ). Conversely, eccentric hamstring peak torque, and subsequently the functional strength ratio, significantly decreased as a function of time during the SAFT<sup>90</sup> ( $P < 0.05$ ). These results in consideration with those from the previous experimental chapter may indicate impaired ability of the hamstrings to eccentrically decelerate the increased velocity of the lower limb during the latter swing phase of the gait cycle when fatigued. Additionally, reduced hamstring flexibility at this time may further increase strain on the muscles and therefore elevate the risk of injury. These impairments in sprint technique and eccentric hamstring strength at the ends of each half of the SAFT<sup>90</sup> appear to support epidemiological observations of increased susceptibility to hamstring injury during the latter stages of each half of matches.

In light of the previous findings, reduced eccentric hamstring strength with fatigue during soccer match-play was deemed to be a significant factor for increased risk of injury. Therefore, maintained eccentric hamstring strength during match-play was deemed crucial for injury prevention. Considering the law of specificity (Kraemer et al., 2002), it was hypothesised that training in a fatigued state may help improve performance in a fatigued state. Consequently, in the final experimental chapter an intervention strategy of performing eccentric hamstring strengthening exercises in a fatigued versus non-fatigued state of soccer training was investigated. Two groups of soccer players performed the training programme bi-weekly over an 8-week period with isokinetic dynamometry testing throughout the SAFT<sup>90</sup> conducted, as in the previous investigation, pre- and post-intervention. Findings revealed that performing eccentric hamstring strengthening exercises in a fatigued state more effectively maintained eccentric hamstring strength and preserved the functional eccH:conQ strength ratio during simulated soccer match-play. This may indicate reduced hamstring injury risk at the time of highest susceptibility to injury during soccer matches.

The findings presented in this thesis may have important implications for future injury prevention and give rise to a new strategy of training in a fatigued state. However, future research should investigate the efficacy of fatigued training for injury prevention at reducing actual injury incidence during match-play. If proven to be successful, this strategy could then be applied to additional injury prevention exercises to help further lower the risk of sporting injury when fatigued.

**Key words:** hamstring strain, match-play, injury prevention, sprinting, eccentric, intervention

# **Chapter 1. General Introduction**



## **1. Introduction**

Soccer is the world's most popular sport with approximately 200,000 professional and 240 million amateur players (Junge and Dvorak, 2004a). On average, players effectively incur one performance limiting injury per year, with 47% of players forced to retire from professional football as a result of an acute or chronic injury (Drawer and Fuller, 2002). Indeed, investigations into senior male professional soccer players have identified an incidence rate of 0.5-45 injuries per 1000 hours of practice and games (Inklaar, 1994a).

Of the most common injuries in soccer, hamstring strains are well recognised by medical personnel, coaches and players as a significant concern within the modern game (Woods et al., 2004). The English Football Association (FA) recently reported an average of 18 days and three competitive matches to be missed per hamstring strain (Woods et al., 2004). Furthermore, the re-injury rate was reported as almost double (12% versus 7%) the rate for all-injuries (Woods et al., 2004). The cost of this not only impairs performance, but also contributes to the average annual world-wide medical cost of soccer injuries at 30 billion United States Dollars (USD), and in professional English soccer approximately 70 million USD per season (Giza and Micheli, 2005). Consequently, the vast financial implications to clubs and players through lost playing time suggest that more effective injury prevention programmes are required.

The incidence rate of hamstring strains has shown an increase over the past 20 years. They are currently reported as the most common injury to professional soccer players with a prevalence rate of 12-15% of all injuries (Hawkins et al., 1999; Hawkins et al., 2001; Woods et al., 2004; Häggglund et al., 2005; Sheppard and Hodson, 2006). The injury is predominantly sustained through non-contact mechanisms (91%), with 57% incurred whilst

running (Woods et al., 2004). Furthermore, almost half (47%) of all hamstring strains occur during the last third of the first and second halves of matches (Woods et al., 2004), suggesting fatigue as a potential predisposing factor to injury.

Research has attempted to investigate the effect of soccer-specific fatigue on risk factors for hamstring strains including muscular strength and imbalances (Rahnama et al., 2003; Greig, 2008), along with potential mechanisms of injury such as sprinting (Pinniger et al., 2000). Soccer-specific fatigue can be defined as the physiological and mechanical fatigue experienced during match-play (Stølen et al., 2005). Physiological fatigue is generally assessed using heart rate, percentage of maximum heart rate, blood lactate and core body temperature (Edwards and Clarke, 2006), whereas mechanical fatigue has been investigated via peak muscular strength of the knee flexors and extensors (Rahnama et al., 2003) and the consequential effect on sprinting performance (Greig et al., 2006). Laboratory-based soccer-specific fatiguing protocols have been developed to measure these various fatigue indices, whilst aid reducing the impact of extraneous variables (eg. temperature, humidity and wind conditions) and improving reproducibility. However, these fatiguing protocols have typically failed to recreate both the physiological responses and mechanical fatigue of match-play. This may be due to failure to accurately replicate the activity profile (Drust et al., 2000a; Nicholas et al., 2000; Thatcher and Batterham, 2004) or multidirectional nature of soccer (Drust et al., 2000a; Thatcher and Batterham, 2004, Greig et al., 2006). Consequently, it is difficult to make inferences about the effect of fatigue to better understand the aetiology of hamstring strains without more accurately simulating the soccer match-play demands. Therefore, additional research using more accurate soccer-specific fatiguing protocols is warranted.

The limitations outstanding, these laboratory-based soccer simulations have been used to investigate risk factors for hamstring strain injuries. Of the various factors, eccentric hamstring strength has been postulated to play a crucial role in hamstring injury susceptibility (Mann et al., 1986). During eccentric contractions, higher tension is generated by the muscle with fewer motor units recruited, thus increasing strain on individual fibres (Fridén and Lieber, 2008). Research has further identified a time specific decline in eccentric hamstring strength at the end of each half of match simulations (Rhanama et al., 2003; Greig, 2008). In light of this, Mjøslnes and colleagues (2004) subsequently employed eccentric hamstring strengthening exercises at the beginning of soccer training, and showed the intervention to improve eccentric hamstring strength (Experimental = 11% versus Control = 0% improvement; Mjøslnes et al., 2004). When this strategy has been investigated (Árnason et al., 2008) on actual hamstring injury incidence rates however, findings revealed no positive effect on hamstring injury prevention during soccer matches. This may be a result of inadequate soccer-specific fatiguing protocols (as mentioned previously), or may be due to the approach to exercise training. For example, different timing strategies may cause alternate improvements and adaptations in muscular strength gains. Specifically, Kraemer et al. (2002) has suggested that training in a fatigued state may better preserve muscular strength. However, this is yet to be investigated in a controlled laboratory environment.

It was therefore the aim of this thesis to investigate the effect of soccer-specific fatigue on markers of hamstring injury risk using a new multidirectional soccer-specific fatiguing protocol. This fatiguing protocol was developed to simulate modern day match-play, and based on 2007 English Championship Level matches (Prozone<sup>®</sup>). The protocol was then used to investigate the fatiguing effect on sprinting kinematics and isokinetic hamstring

strength, with particular consideration to the hamstring and quadriceps muscular imbalance (Dauty et al., 2003). Due to the reduced eccentric hamstring muscle strength subsequently observed at the end of each half of the fatiguing protocol, an appropriate intervention programme in the prevention of hamstring strains was developed.

The significance of this thesis is to add to the current body of work and understanding regarding the aetiology and mechanisms of hamstring strains in soccer. By applying a newly developed multidirectional soccer simulation to investigate the effects of soccer-specific fatigue on hamstring injury risk factors, more relevant and significant findings may be revealed to provide a better understanding of this relationship. Finally, by using this knowledge to form the foundations with which to develop new hamstring injury prevention strategies, potentially greater injury prevention benefits may be observed in the future.

## **Chapter 2. Literature Review**

## **2.1 Introduction**

There have been numerous epidemiological studies documenting general soccer injury profiles (Luthje et al., 1996; Hawkins et al., 2001; Sheppard and Hodson, 2006) as well as studies examining individual injuries, including knee anterior cruciate ligament (ACL) (Arendt and Dick, 1995; Bjordal et al., 1997) and lateral ankle ligament injuries (Giza et al., 2003; Woods et al., 2003; Andersen et al., 2004a). Considering the specific topic of this thesis however, the following review aims to focus on the epidemiology of hamstring strain injuries in soccer. This considers injury incidence, common mechanisms of injury, and the temporal pattern of injury during the soccer season and actual match-play concerning the influence of fatigue as an injury risk factor.

The biomechanics of hamstring strains are discussed along with aetiological risk factors for injury to identify potentially modifiable factors for future investigation. Of the various injury risk factors, the role of fatigue in hamstring strain susceptibility will be further discussed. This considers fatigue associated with sprinting, the primary mechanism of injury for hamstring strains (Woods et al., 2004), and also soccer-specific fatigue experienced during match-play. In particular, the role of fatigue during matches is discussed by reviewing notational and motion analyses of match-play which is commonly used to describe the work rate profile of soccer, and in respect to the physiological and mechanical stressor demands. This information is then used to critically analyse previous soccer simulations as to their ability to accurately recreate the physiological responses, movement demands and work rate profiles of match-play, and therefore, replicate the environment for injury potential related to soccer-specific fatigue.

## **2.2 Epidemiology of Hamstring Strains in Soccer**

The interest and popularity in soccer has increased considerably over the past decade, and has led to an increased amount of injuries within the sport (Olsen et al., 2004). Hamstring strains in particular appear to have shown an increased incidence rate over recent years. Thus, hamstring strains have become established as a major concern in modern soccer, with more effective injury prevention programmes recommended (Rahnama et al., 2002). Information regarding hamstring injury epidemiology can be used to identify factors involved in the incidence, classification, mechanism and temporal pattern of injury with which to subsequently inform intervention strategies.

### **2.2.1 Incidence of Hamstring Strains**

The incidence rate of soccer injuries is commonly defined as the number of injuries per 1000 hours of player activity time, or number of injuries per 1000 athlete exposures (Wong and Hong, 2006). Soccer injury audits conducted in the early 1980's and 1990's reported a prevalence rate of hamstrings strains at ~6% (Ekstrand and Gillquist, 1983a; Nielsen and Yde, 1989) of total injuries, while knee and ankle ligamentous sprains sustained through contact mechanisms were associated with the highest rates of injury (Ekstrand and Gillquist, 1983a; Nielsen and Yde, 1989). However, over time the rate of hamstring strains has more than doubled, with recent injury audits reporting them as 13-15% of all injuries (Woods et al., 2004; Hägglund et al., 2005; Wällden et al., 2005a and 2005b; Sheppard and Hodson, 2006).

The incidence rate of hamstring strains has also varied depending on the subject population. Hamstring strains are particularly prevalent in senior male players within the higher divisions of soccer (McGregor and Rae, 1995; Árnason et al., 1996; Hawkins and Fuller,

1999; Hawkins et al., 2001; Volpi et al., 2004), whereas youth players sustain a greater proportion of contusion and ligamentous sprain type injuries (Maehlum et al., 1986). There may also be evidence to suggest that English professional players are at a greater risk of hamstring strain injuries compared with their European counterparts. Hägglund et al. (2005) recently reported muscular strain injury rates for professional Danish and Swedish soccer players as 21% and 22% respectively, whereas the corresponding incidence rate to English players reported by Hawkins et al. (2001) was 35% of total injuries. This incidence rate discrepancy, coupled with the chronological disparity, led to the focus of this body of work on English senior, high-level, male soccer players.

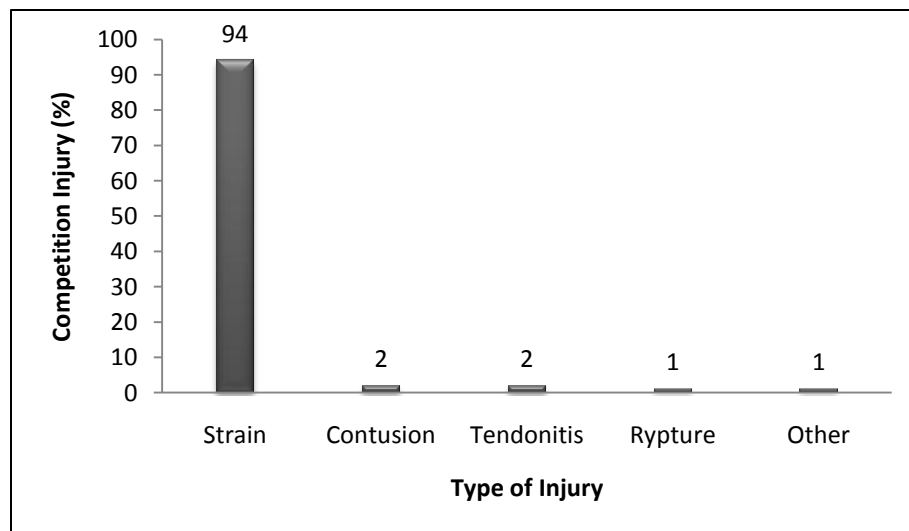
### **2.2.2 Classification of Hamstring Injuries**

Muscle injuries can be classified as either direct or indirect, depending on the trauma mechanism; direct forms are lacerations and contusions; and the indirect form is strain (Petersen and Hölmich, 2005). Indirect muscle injuries may be further classified as either complete: typically an avulsion injury where the muscle tendon pulls off a piece of bone from its proximal or distal attachment, or incomplete: tearing of some of the muscle fibres (Petersen and Hölmich, 2005). Muscle strains can also be divided into three grades according to the severity of injury (Ekstrand and Gillquist, 1983a):

- Mild (first degree): a tear of a few muscle fibres with minor swelling and discomfort and with no, or minimal, loss of strength and restriction of movements.
- Moderate (second degree): greater damage of muscle with a clear loss of strength.
- Severe (third degree): a tear extending across the whole cross section of the muscle resulting in a lack of muscle function.



Muscular strains have been reported to account for 81% of all thigh injuries in soccer (Hawkins et al., 2001), and up to 94% of hamstring injuries (Woods et al., 2004; Figure 2.1). Strains to the hamstring group predominantly occur at the muscle-tendon junction (Garrett, 1996), with diagnosis of injury based on accurate subjective history and by completion of a physical assessment. Examination using magnetic resonance imaging is performed in only 5% of cases in professional soccer players (Woods et al., 2004).



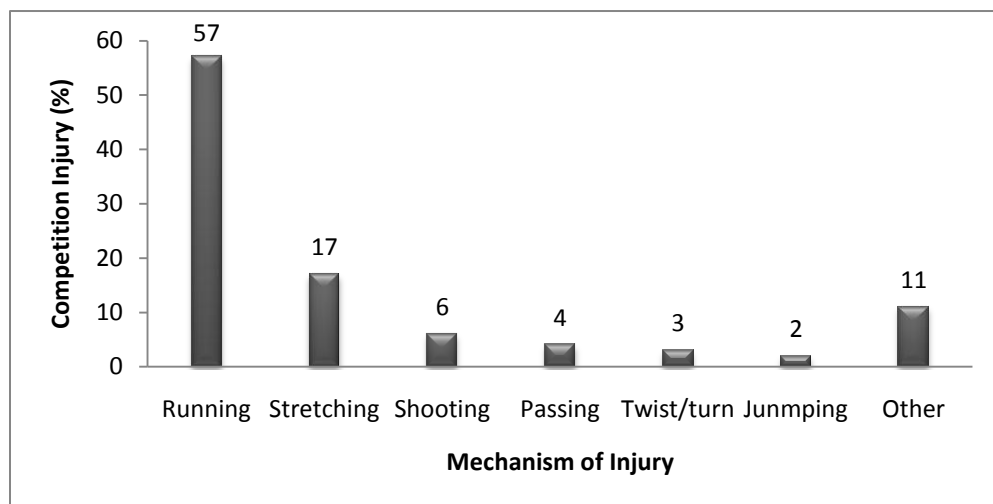
**Figure 2.1.** Classification of hamstring injuries (recreated from Woods et al., 2004)

Strains to the hamstring muscle group have been reported to occur at a ratio of 3:1 when compared with strains to the quadriceps muscle group (Hawkins et al. 2001). Wällden et al. (2005b) further supported this finding, revealing increased incidence to injury of the hamstring muscle group when compared to their antagonistic group (67 versus 36 respectively). In addition, the biceps femoris muscle is the most frequently injured of the hamstrings, accounting for 53% of all hamstring strains while the semimembranosus and the semitendinosus constitute a much lower percentage of 13% and 16% respectively (Woods et al., 2004). However, in the aforementioned study by the English FA (Woods et al., 2004), 19% of all hamstring injuries reported were unspecified in their diagnosis, and therefore, figures should be taken with an element of caution.

### 2.2.3. Mechanism of Injury

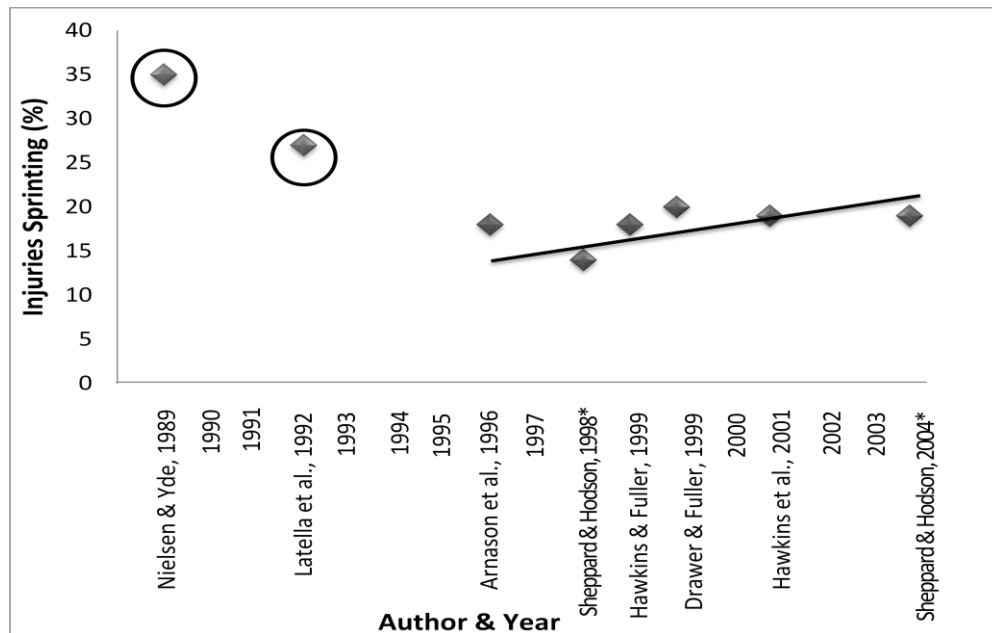
Mechanisms of injury in soccer are commonly divided into either contact or non-contact (Krosshaug et al., 2005). Contact injuries may further be subdivided into: direct (a direct blow to the lower extremity of the injured player; thigh knee or lower leg), or indirect (where the injured player is held, hit or pushed in a body region other than the lower extremity; Krosshaug et al., 2005). However, although the distinction between direct and indirect contact injuries may have important implications for preventing injury, and thus intervention programmes, this categorisation is seldom utilised.

Epidemiological research has found common relationships between injury mechanisms and some of the most prevalent soccer injuries. Muscular strains to the thigh region are frequently associated with non-contact mechanisms (Hawkins et al., 2001; Woods et al., 2004). Hamstring muscle strains are often observed in sports involving sprinting and jumping activities (Stanton and Purdam, 1989). In soccer, their mechanism of injury is predominantly attributed to running/sprinting, reported by the English FA as the cause of 57% of all hamstring strains (Woods et al., 2004; Figure 2.2).



**Figure 2.2.** Mechanism of hamstring injuries (recreated from Woods et al., 2004)

Early injury audit studies revealed an extremely high rate of 27-35% (Nielsen and Yde, 1989; Latella et al., 1992) of total injuries caused by running. This rate (Figure 2.3) then appears to rapidly decrease between 1989 and 1996 before levelling out over the next eight years, although remaining relatively high as the primary non-contact injury mechanism.



**Figure 2.3.** Percentage of injuries caused by sprinting as a total of all-injuries (\* represents data obtained from a number of seasons within the same study)

However, the early results reported (circled in Figure 2.3) may be misleading. The term “running” employed within these studies may have been used as a blanket term to encompass additional mechanisms, such as twisting, turning or stretching, as was subdivided for in more recent investigations. A trend line added to the graph, excluding the earlier two results, reveals a more constant increase in the proportion of injuries sustained through sprinting over time. This finding may be attributed to differences within study methodologies and injury mechanism definitions, which should be standardised in future investigations to allow for more accurate comparisons. Regardless, as the speed and intensity have increased in the modern game, it is perhaps not surprising that there has been

an increase in hamstring strains from 6% of total injuries in 1983 (Ekstrand and Gillquist, 1983a) to 13% in 2006 (Sheppard and Hodson, 2006).

#### **2.2.4. Re-injury Rate**

An audit into injuries in professional soccer by the English FA reported recurrent injuries to account for 7% of all injuries (Hawkins et al., 2001). The study also revealed that a subsequent injury was significantly ( $P < 0.05$ ) biased towards the locality of the preceding injury and higher for professional (22%) than youth (10%) players (Hawkins et al., 2001). Comprising the types of re-injury, muscular strains formed 48%, with 82% of recurrent thigh strains to the posterior thigh (Hawkins et al., 2001). Woods et al. (2004) more recently recorded a 12% re-injury rate for hamstring strains, significantly greater than the average re-injury rate of 7% previously reported by the English FA (Hawkins et al., 2001).

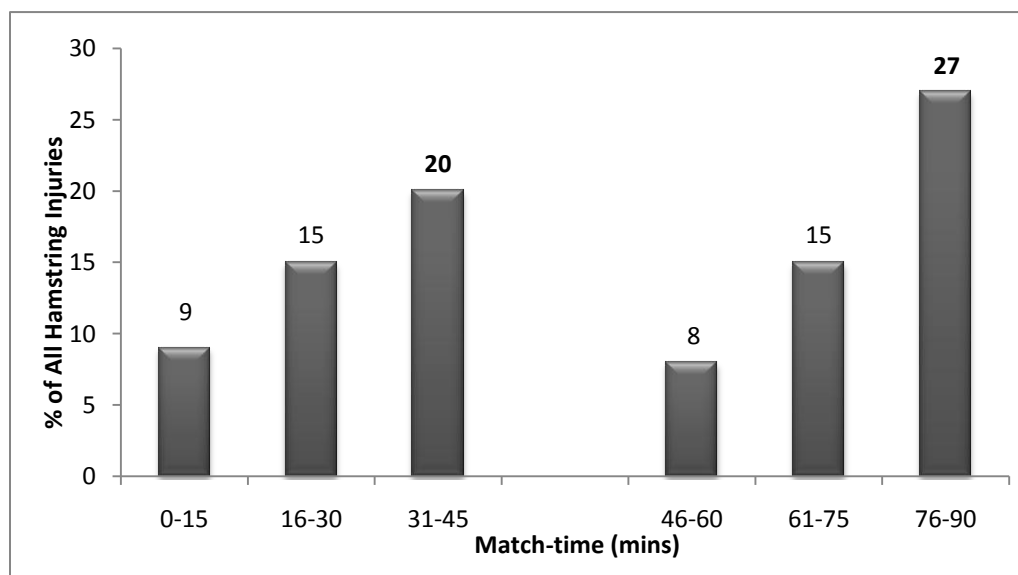
Although the exact pathophysiology of re-injury remains unknown, a major trauma resulting in an initial injury often requires only a subsequently minor trauma to cause re-injury (Nielsen and Yde, 1989; Woods et al., 2003). The increased risk of injury during non-contact mechanisms, including sprinting, may suggest incomplete rehabilitation following the initial injury (Árnason et al., 1996). Therefore, to reduce the risk of re-injury, specific rehabilitation goals to be set and specific return-to-play criteria established (Hawkins et al., 2001).

#### **2.2.5. Temporal Pattern of Hamstring Injuries**

The temporal pattern of soccer injuries can be investigated in relation to the timing of injuries both over a playing season and throughout the course of individual match-play (Hawkins et al., 2001). Within the English season, a high proportion of hamstring strains have been observed during preseason training and following the closed season (Woods et

al., 2004), which concurs with the temporal pattern observed for all injuries (Hawkins et al., 2001; Sheppard and Hodson, 2006). This may be due to players losing fitness during the closed season, thus rendering them less able to withstand the stresses associated with pre-season training (White et al., 1988). In addition, a high proportion of hamstring strains have been observed towards the latter part of the competitive season (Woods et al., 2004). Reduced emphasis on players' conditioning or players becoming both physically and mentally fatigued at this time may explain this finding (Sheppard and Hodson, 2006). However, at present only a single soccer injury audit (Woods et al., 2004) has investigated the temporal pattern of injury in soccer solely concerning hamstring strains, therefore additional research is warranted.

The temporal pattern of injury during match-play has also revealed a potential association of increased incidence of injury with fatigue. Woods et al. (2004) observed nearly half (47%) of all hamstring injuries were sustained during the final third of the first and second halves of matches (Figure 2.4). The authors concluded from this information that fatigue may be a potential predisposing factor for injury (Woods et al., 2004).



**Figure 2.4.** Temporal pattern of hamstring injuries (recreated from Woods et al., 2004)

Hamstring strains are predominantly incurred during sprinting (Woods et al., 2004). Specifically, the strains have been associated with asynchrony to individual muscles within the hamstring group (Pinniger et al., 2000). This may alter the complex neuromuscular coordination pattern that occurs during running (Verrall et al., 2001). However, it should be considered that previous research has not investigated this hypothesis using fatiguing protocols reflective of the mechanical and physiological demands of soccer match-play.

#### **2.2.6. Summary**

Epidemiological research over the past 35 years has documented the extent of the sports injury problem concerning hamstring strains to senior high-level male soccer players. Hamstring strains are the most prevalent non-contact injury to modern day professional players, constituting up to 15% of total injuries (Hägglund et al., 2005) and with a high tendency to reoccur. They are commonly sustained whilst sprinting, and the temporal pattern of match injury rates has revealed an increased incidence of injury during the latter stages of each half, therefore suggesting that fatigue may play a crucial role in injury susceptibility.

Considering the high incidence and subsequent cost of hamstring strains, the evidence discussed substantiates the requirement for more effective injury prevention strategies. Van Mechelen et al. (1992) advocated that with greater understanding of the mechanisms and aetiology of the sports injury problem, it may enable more effective intervention strategies to be identified and introduced to reduce the incidence of injury. Therefore, additional focused research and knowledge is warranted regarding injury risk factors (perhaps specifically concerning the role of fatigue in light of previous findings) and the primary mechanism of injury (sprinting).

### **2.3. Biomechanics of Muscle Strain Injuries**

This section will be devoted to the fundamental mechanisms of muscle strain injuries, discussing the biomechanics and physiology of strains.

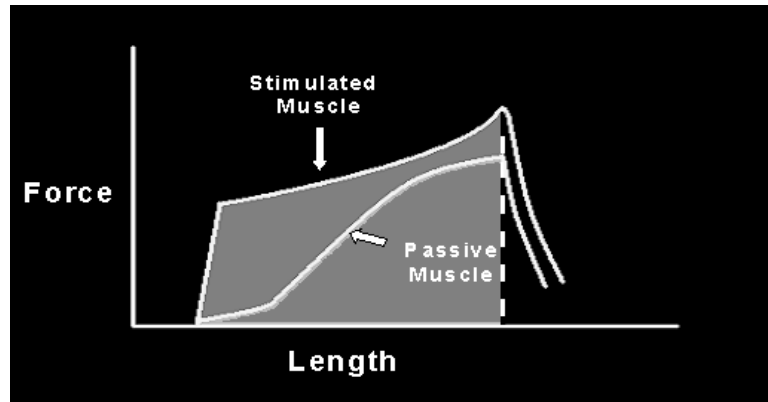
#### **2.3.1. Biomechanics of Muscle Strains**

Muscular strains account for up to 37% of all injuries in professional soccer (Hawkins et al., 2001). A muscle strain is characterised by a partial or complete tear of the muscle-tendon unit, with subsequent localised pain and weakness with activity (Garrett, 1990). Brewer (1960) originally proposed that certain muscles may be more susceptible to injury than others, with muscles acting over two joints at greatest risk of injury.

It is generally agreed by clinicians that muscle strains occur when a muscle is either stretched passively or activated during stretch (Zarins and Ciullo, 1983). They have been investigated in laboratory experiments whereby forces and strain have been created and measured for isolated muscles affecting individual joints in vivo during the gait cycle (Mann and Prague, 1980). One such study (Garret, 1996) conducted laboratory experiments into passive and active stretch, and non-disrupt injury mechanisms using rabbit hind limb muscles. In the first of a series of experiments, muscles stretched passively to failure were observed to tear at the proximal or distal muscle-tendon junction independent of strain rate, muscle length or architecture (Garrett, 1996). Findings also revealed that the forces needed to cause failure were several times the magnitude produced during active maximal isometric contractions, suggesting passive forces should be considered (Garrett, 1996).

In the subsequent investigation into injuries caused by active stretch, hind limb muscles were isolated and stretched to failure, with the muscles either activated by titanic stimulation, submaximal stimulation or with no stimulation (Garrett, 1996). Again, failure

occurred at the muscle-tendon junction for all conditions, with activated muscles generating 15% greater force at failure and 100% more force absorption (Garrett, 1996; Figure 2.5).



**Figure 2.5.** Relative differences in force absorption to failure in stimulated versus passive muscle preparations shown (adapted from Garrett, 1996). Force absorbed shown as area under each length-tension deformation curve.

Garrett (1996) subsequently concluded that passive elements of muscles have the ability to absorb force, which is enhanced when the muscle is activated and therefore providing better protection from injury. Consequently, any condition which may diminish the ability of a muscle to contract, and therefore absorb force (ie. fatigue and weakness) may increase susceptibility to muscle strain injury (Garrett, 1996).

The final study by Garrett (1996) regarding non-disruptive injuries was investigated by initially executing incomplete disruption (muscle strain) to the hind limb muscle-tendon junctions. The muscles were then stretched following a 7-day period and recorded to produce only 77% of the contralateral control muscles' tensile strength, significantly lower than the 90% produced by non-stretched muscles ( $P < 0.05$ ). This was reported to indicate a change in linearity of the force-displacement curve of a stretched, inactivated muscle, indicating plastic deformation had occurred to alter its material structure (Garrett, 1996). Furthermore, as strains are partly caused by stretch, the subsequent loss in tensile strength may place muscles at increased susceptibility to re- injury (Garrett, 1996).



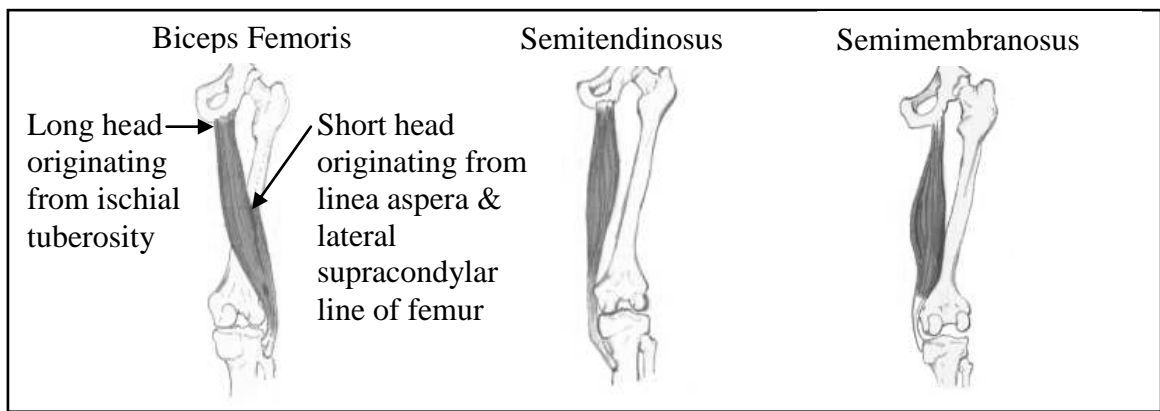
The findings from the investigations by Garrett (1996) should be considered in light of being conducted using rabbit hind limb muscles, therefore the clinical applications of the findings to humans may be questionable as animal models might not be transferrable (Thomas and Campbell, 2000). Nevertheless, it may be considered that muscles have a strain threshold for both passive and active injury, resulting from excessive stretch or stretch whilst activated (Kirkendall and Garrett, 2002). In addition, stronger muscles may be better able to protect from injury by absorbing more force (Garrett, 1996). Therefore, muscle imbalances may be a predictor of injury for the weaker muscle (Garrett et al., 1987). Muscles may also be weaker following injury and thus at increased risk of re-injury, especially with incompletely healed strains.

#### **2.4. Aetiology of Hamstring Strain Injuries**

In this section, the anatomy of the hamstring muscle group and proposed aetiological risk factors for injury will be discussed.

##### **2.4.1. Anatomy**

The hamstring muscle group comprises of three separate muscles: biceps femoris, semimembranosus and semitendinosus. All attach proximally at the ischial tuberosity, although the biceps femoris has two heads with the second, short head originating from the linea aspera and lateral supracondylar line of the femur (Moore and Dalley, 1999). The semimembranosus inserts into the posterior part of the medial tibial condyle and the oblique popliteal ligament, the semitendinosus into the antero-medial surface of the tibia with gracilis and sartorius muscles forming the pes anserine group, whilst the biceps femoris attaches onto the head of the fibula (Moore and Dalley, 1999; Figure 2.6).



**Figure 2.6.** The hamstring muscles (adapted from Agre, 1985)

Semimembranosus and semitendinosus are located on the medial aspect of the posterior thigh, whilst biceps femoris lies more laterally (Koulouris and Connell, 2006). Since the muscles cross two joints (hip and knee), they have a dual role acting as either a hip extensor or knee flexor, and can only localise their contraction to one joint if either of the antagonist muscle groups (quadriceps and iliopsoas) contracts (Koulouris and Connell, 2006).

#### **2.4.2. Aetiology of Hamstring Strains**

The foundations of injury prevention strategies are based on a good understanding of both causative and predisposing factors for injury, especially those that can be modified (Taimela et al., 1990). Several risk factors have been hypothesised for hamstring strain injuries, and although injury may occur due to a single factor, it is more likely to be the result of an interaction between multiple risk factors (Hoskins and Pollard, 2005a). However, individual factors associated with hamstring strain injuries will be discussed in association with their respective estimated roles.

##### **2.4.2.1. Flexibility**

If the hamstring musculo-tendinous unit lacks sufficient flexibility, whether due to lack of stretching, poor posture or poor body biomechanics, it may be stretched beyond its ability

to elongate (Baker, 1984; Witvrouw et al., 2003). Witvrouw et al. (2003) examined muscle flexibility as a risk factor for developing muscle strain injuries in professional male soccer players. A stepwise logistic regression analysis identified hamstring muscle flexibility as an intrinsic risk factor for musculoskeletal injuries. Furthermore, a significant correlation was found between players with decreased hamstring flexibility and the occurrence of a hamstring injury ( $P = 0.02$ ). Although the study failed to note the circumstances surrounding the inciting injury event, the findings support observations of reduced muscle flexibility and increased injury risk, with 11% of all soccer injuries previously reported as related to muscle tightness (Ekstrand and Gillquist, 1983b).

In consideration of the potential relationship between reduced flexibility and hamstring injury risk, Hartig and Henderson (1999) conducted a prospective intervention study to examine the effect of a flexibility protocol on injury incidence. Two groups of subjects were followed over a 13-week period with one group incorporating a hamstring stretching routine into their pre-exercise warm-up. Results indicated that the intervention group demonstrated significantly increased flexibility and subsequent lower injury incidence compared with the control group (incidence rate 16.7% v 29.1%;  $P < 0.05$ ). The authors concluded that flexibility was a significant risk factor for hamstring strains, and that increasing muscle flexibility through stretching may decrease injury risk. However, the subject population of military trainees are exposed to different physical stresses and demands due to the differing nature of activity compared with soccer players.

Lack of flexibility has not, however, been conclusively linked as a risk factor for hamstring strain injuries. Árnason et al. (2004a) conducted a prospective cohort study using professional soccer players to identify injury risk factors. Findings failed to identify hamstring flexibility as a risk factor for hamstring strains, which support earlier results by

Hennessey and Watson (1993). The divergence in findings concerning the role of flexibility in hamstring injury risk may be due to a lack of clarity in injury definitions or research design, especially when distinguishing between various types of flexibility protocols employed (Gleim and McHugh, 1997). Information on muscle flexibility as a risk factor for hamstring strains in soccer players appears inconclusive and prospective studies into the area scarce. Although flexibility may be involved in a complex, interactive, multifactorial relation with muscle strain injury, its function appears further confounded by the wide variety of flexibility protocols as observed in English professional soccer (Dadebo et al., 2004). Therefore, the role of flexibility as an aetiological risk factor for hamstring strains and in reducing their injury incidence remains contentious, with further research warranted.

#### **2.4.2.2. Muscle Strength and Balance**

Muscle strength deficiency has been proposed as an important risk factor for hamstring strain injuries (Worrell, 1994). Specifically, strength imbalance between dominant and non-dominant hamstring muscles and between quadriceps and ipsilateral hamstring muscles has been related to hamstring muscle weakness (Burkett, 1970). Eccentric hamstring strength has received most attention within this area, as eccentric actions are seen as an integral part of the functional repertoire of the hamstring muscles and a key factor related to their potential for injury (Mann et al., 1986).

Hamstring strength deficiencies as a risk factor for injury have received substantial research attention in regard to the strength balance between the hamstrings and quadriceps muscle groups (Burkett, 1970; Christensen and Wiseman, 1972). It has been reported that relative weakness of hamstrings to quadriceps strength of the same limb is a risk factor for hamstring injury (Burkett, 1970; Christensen and Wiseman, 1972; Dauty et al., 2003).

This strength imbalance is reported by means of calculating a ratio of the isokinetic hamstring muscle strength relative to quadriceps strength (H:Q). The traditional method of calculating the ratio is done by using concentric hamstrings strength and concentric quadriceps strength (conH:conQ), whereas a more recent “functional” ratio utilises eccentric hamstring strength (eccH:conQ). It remains unresolved as to which ratio is most valid. However, Dauty et al. (2003) reported only the functional H:Q strength ratio as able to identify soccer players with previous hamstring injury history. This may support the notion that eccentric hamstring strength may be of greater significance in terms of hamstring injury potential (Mann et al., 1986). In contrast, Bennell et al. (1998) reported that neither H:Q strength ratio was able to identify players at risk for subsequent hamstring strain injury. Thus, it also remains unresolved as to whether strength disorders are the consequence of injury, a causative factor, or both (Hoskins and Pollard, 2005a).

An additional factor to consider when comparing results of H:Q ratios between studies is the standard of subjects. Cometti et al. (2001) investigated the H:Q ratios at different levels of play in French soccer players. Results revealed that elite players demonstrated significantly higher H:Q strength ratios compared with sub-elite players at a range of angular velocities between 2.09 and 5.23 rad·s<sup>-1</sup> ( $P < 0.05$ ). This finding was attributed to increased training load and specialised strength training programmes of elite players, thus resulting in improved strength balances compared with amateurs. Therefore, it could be speculated that amateurs may be at greater risk of hamstring strain injury than professionals, although this is yet to be confirmed by epidemiological research.

It is furthermore difficult to compare findings from studies investigating muscular strength and injury, as different planes of motion and test speeds may affect accurate comparison (Murphy et al., 2003). The validity of utilising isokinetic dynamometry to measure strength

may also be limited when extrapolating the results to sporting context involving multi-joint movements and higher limb velocities (Baltzopoulos and Gleeson, 2001). Therefore, tests performed non-weight-bearing may fail to duplicate the demands of sporting activity.

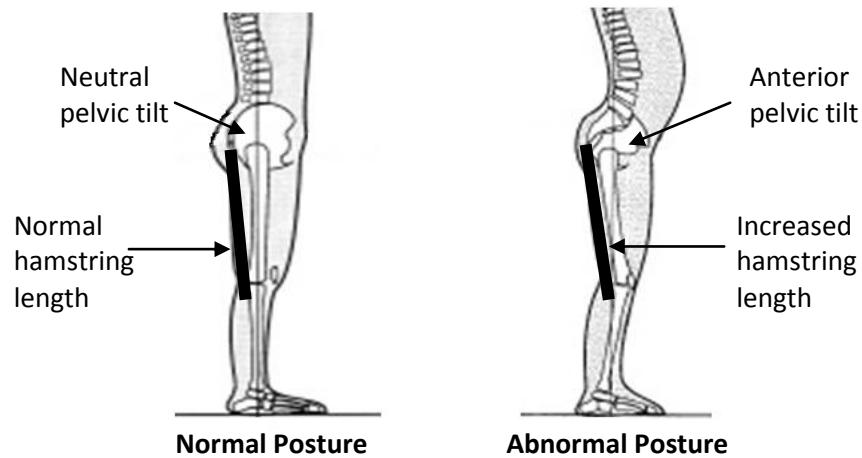
If eccentric hamstring strength is an important factor for hamstring injury risk, it could be considered crucial for hamstring injury prevention strategies. In light of this, Askling et al. (2002) examined the effect of preseason eccentric hamstring strength training in elite Swedish soccer players. Results showed significantly fewer hamstring injuries in the intervention group, with 10 of the 13 injuries reported in the control group ( $P < 0.05$ ). However, the authors acknowledged the limitation of low subject number ( $n = 30$ ) in the study. Therefore, further investigation is warranted to clarify the relationship between eccentric hamstring strength and subsequent injury occurrence.

#### **2.4.2.3. Body Mechanics and Dysfunction**

Biomechanical principals dictate that restriction or tension in one part of a kinetic chain will create an increased load on other parts of that same chain (Comerford and Mottram, 2001). This may result in either instant macro-trauma, or have the repetitive cumulative effect of micro-trauma and eventually culminate in strain (Wallden and Walters, 2005). It has been hypothesised that tension or restriction elsewhere in the functional chain of the hamstring muscles may result in their recurrent nature (Wallden and Walters, 2005). In relation to soccer, this could be related to tension of the anterior thigh and hip flexors, thus increasing the amount of stretch placed on the hamstrings.

Aberrant lumbar-pelvic mechanics, such as lumbar lordosis, sway back posture and anterior pelvic tilt, have been indirectly linked as an aetiological risk factor for hamstring injuries (Hoskins and Pollard, 2005a). A common pattern of muscular imbalance in the lower limb

is known as the lower crossed syndrome (Janda, 1996). It was proposed by Janda (1996) that tight hip flexors and lumbar erector spinae in conjunction with weak, inhibited gluteal and abdominal muscles, result in an anterior pelvic tilt. This may subsequently alter hamstring biomechanics and function by elongating the entire hamstring musculotendinous unit (Janda, 1996; Figure 2.7).



**Figure 2.7.** Diagram showing normal and abnormal posture with associated effect on pelvic tilt and hamstring muscle length

Cibulka et al. (1986) supported this hypothesis, with increased uni-lateral anterior pelvic tilt found to be a significant risk factor for hamstring injury ( $P < 0.05$ ). However, low subject number ( $n = 20$ ) was considered a substantial limitation to the investigation. In a prospective study, Watson (1995) also reported excessive lumbar lordosis and sway back posture to be related to thigh (hamstring and quadriceps) muscle injuries. A posture of increased lumbar lordosis is understood to be caused by excessive anterior pelvic tilt, related to over-development of the psoas muscles used in kicking (Rasch and Burke, 1978). It was hypothesised by Watson (1995) that this may consequently place extra strain on the hamstrings, which are often weak in athletes with excessive lordosis.

At present, it is unclear as to whether improving body mechanics can result in hamstring injury prevention. Currently, only one case study (Hoskins and Pollard, 2005a) using

Australian Rules Football (ARF) players has investigated this matter, showing full recovery and no hamstring re-injury after improving lumbar-pelvic mechanics. There is clearly a need for agreement in the literature regarding measurement of the characterisation of abnormal alignment and body mechanics as well as a standardisation of the methods to measure them. Subsequently, further prospective studies are required to investigate such body mechanics as aetiological risk factors for hamstring strains.

#### **2.4.2.4. Warm-up**

Warm-up prior to exercise extensive enough to cause increased muscle temperature has been emphasised to prevent muscle strain injury (Garrett, 1990) by facilitating increased connective tissue extensibility via modifications of viscoelastic properties (Garrett, 1996). A 1°C increase in muscle temperature has been found to increase the muscle length before failure (Kirkendall and Garrett, 2002). Safran et al. (1988) investigated the relationship between warm-up and injury potential in an animal model, whereby muscles were held isometrically and tetanically stimulated for 10-15 s to provoke a 1°C rise in muscle temperature. As a result, muscles produced greater force and were able to stretch further before failure. Pre-exercise warm-up and stretching were consequently proposed as crucial for injury prevention due to the theory that the capability of the musculo-tendinous unit to absorb force is directly proportional to resting length and muscle temperature (Taylor et al., 1990; Safran et al., 1988). Insufficient warm-up and stretching before exercise may alternatively result in the muscle being cooler and less flexible. Neuromuscular coordination may also be impaired, resulting in de-synergic muscle contraction (Agre, 1985).



In order to investigate the efficacy of warm-up for the prevention of hamstring strains, Heiser et al. (1984) conducted a prospective intervention study using intercollegiate soccer players. After adopting a universal warm-up programme incorporating strength, flexibility and conditioning, a significant reduction in hamstring incidence was observed ( $P < 0.05$ ). However, by using a multifaceted warm-up programme it is difficult to delineate the impact of each individual aspect on the reported injury reduction. Cross and Worrell (1999) examined the efficacy of an individual warm-up lower limb flexibility protocol on the incidence of lower extremity musculo-tendinous strains in college soccer players. The intervention was incorporated into the second of a 2-season testing period, with results later showing a significant reduction in the number of lower extremity musculo-tendinous strains for the intervention season ( $P < 0.05$ ). However, as injuries were not individually specified, it is impossible to establish the exact effect of the warm-up on hamstring injuries.

Research is not unequivocal regarding the effect of warm-up in preventing hamstring strain injuries. Verrall et al. (2003) reported a continued risk of hamstring injury after significant warm-up. Moist heat packs applied to the muscle group to simulate a warm-up situation failed to significantly affect hamstring muscle flexibility, thereby indicating no beneficial effect at increasing muscle temperature passively (Safran et al., 1988). This may provide indirect evidence for a kinetic chain rather than a localised muscle cause of injury (Sawyer et al., 2003). Alternatively, stretching as part of the warm-up was alleged by Shrier (2000) to actually increase injury risk, as even mild stretching can cause damage at the cytoskeletal level. At present, due to contradicting evidence presented regarding the relationship between warm-up and hamstring injury prevention further research is required.

#### **2.4.2.5. Previous Injury and Inadequate Rehabilitation**

There is strong evidence that a prior injury in conjunction with inadequate rehabilitation is a risk factor for re-injury (Árnason et al., 1996 and 2004a; Hawkins et al., 2001; Murphy et al., 2003; Hägglund et al., 2005). Previous injury may lead to an increased risk of re-injury by contributing to muscular imbalance and weakness, with the fear of re-injury further causing the athlete to use altered muscle-recruitment strategies (Murphy et al., 2003).

In soccer, re-injury is a major concern, with early findings by Ekstrand and Gillquist (1983a) reporting a minor injury preceded a more serious injury within two months in 26% of players. More recently, Dvorak et al. (2000) identified previous injury and inadequate rehabilitation as significant risk factors ( $P < 0.05$ ) for re-injury when studying 398 players over one-year. However, the results did not specify predictive values of risk factors for specific injuries. In a similarly designed prospective cohort study investigating injury risk factors in male professional players, Árnason et al. (2004a) subdivided specific injuries to establish individual risk factors. Of the 12 categorical risk factors tested concerning hamstring strains, only history of previous injury was identified as a significant risk factor for a new strain on the same limb. Indeed, the English FA revealed a re-injury rate of 12% for hamstring strains, substantially greater than the 7% for all injuries (Woods et al., 2004).

The high re-injury rate for hamstring strains is perplexing, given the fact that it is generally considered that skeletal muscle is capable of virtually complete regeneration after injury (Best, 1997). Although the exact pathophysiology of re-injury remains enigmatic, it has been linked to the inability of medical personnel to assess the severity of initial damage, and the premature return to competition during the remodelling phase of healing (Hoskins and Pollard, 2005a). Re-injury may be related to scar tissue formation, as with ineffective

treatment, scar tissue and adhesions will accumulate, resulting in a less compliant area (Hoskins and Pollard, 2005a). Another theory proposed by Turl and George (1998) considers the plasticity of the nervous system, as recurrent hamstring injuries have been hypothesised to lead to sensitisation of the dorsal horn of the spinal cord. This may predispose re-injury by altering hamstring and gluteus maximus firing patterns (Lehman et al., 2004). Perhaps more simply however, players may be at a greater risk of re-injury by returning-to-play before full recovery of flexibility, strength, endurance, and coordination.

Overall, it is generally accepted that previous injury and inadequate rehabilitation are strong aetiological risk factors for hamstring strains (Agre, 1985; Árnason et al., 2004a; Hoskins and Pollard, 2005a). Therefore, primary prevention of the initial injury is crucial, as is the understanding and application of safe and effective rehabilitation programmes prior to returning players to sport. However, the use of over-aggressive rehabilitation designed to return a player prematurely to competition may be too stressful for the muscle, thereby risking further re-injury (Garrett, 1996).

#### **2.4.2.6. Age**

Age is perhaps the most established risk factor for hamstring strains, although like previous injury, is non-modifiable. It seems reasonable to suppose that age would be a risk factor for injury, as older players have increased exposure over time within their risk environment (Murphy et al., 2003). In English soccer, Woods et al. (2004) identified players in the youngest age group category (17-22 years old) sustain significantly fewer hamstring strains than players in the older category (26-35<sup>+</sup> years old;  $P < 0.01$ ). Whereas in ARF players, Verrall et al. (2001) reported a 1.3 fold increase in hamstring injury risk per year of increased age. This supports work by Orchard (2001) who observed players older than 23

years as more likely to incur hamstring strains (relative risk = 1.34, 95% CI = 1.14 to 1.57). This finding was attributed to the theory that abnormalities of the lumbar spine are implicated in the development of muscle strains, since the lumbar nerve roots of L5 and S1, which supply the hamstrings, are more likely to be affected by age-related spinal degeneration than the nerve supply of the quadriceps (L2/3/4; Orchard, 2001). This lumbar degeneration may cause L5 and S1 nerve impingement and hamstring fibre denervation, leading to decreased muscle strength, as is especially associated with type II muscle fibres in the hamstrings (Kirkendall and Garrett, 1998). In summary, the evidence suggests senior, high-level male soccer players are at the highest risk of hamstring injury.

#### **2.4.2.7. Race**

An additional non-modifiable risk factor associated with hamstring strains may be race; players of black or aboriginal ethnic origin have been observed to be at increased risk of hamstring strain injury (Woods et al., 2004). The English FA audit investigating hamstring injury epidemiology provided the first evidence that soccer players of black ethnic origin were at a greater risk of sustaining a hamstring injury than Caucasian players (Woods et al., 2004). These findings support previous research using a subject population of ARF players (Verrall et al., 2001), where players of aboriginal descent were reported to be at significantly increased risk of sustaining a hamstring injury than any other race.

It has been proposed that players of black or aboriginal ethnic origin have a greater proportion of type II muscle fibres, associated with increased predisposition to strain injury (Verrall et al., 2001). It was also speculated by Woods et al. (2004) that it is common for players of black origin to have an anteriorly tilted pelvis. Therefore, as athletes with increased anterior pelvic tilt are at increased risk of hamstring strain injury (Cibulka et al.,

1986), this may also explain why players of black origin are at greater risk of hamstring injury (Woods et al., 2004). However, such reasoning is not scientifically proven.

#### **2.4.2.8. Fatigue and Aerobic Endurance**

Fatigue has been associated as a risk factor for injury, causing altered muscle recruitment patterns which may change the distribution of forces acting on muscular structures (Murphy et al., 2003). The temporal pattern of hamstring injuries during soccer match-play observed by Woods et al. (2004) further indicate increased risk of injury when fatigued. Also, as many of the injuries were sustained whilst running (57%), it was further suggested that any factor that may alter the complex neuromuscular coordination pattern that occurs during the running cycle may cause injury (Verrall et al., 2001).

Fatigue towards the ends of each half of a soccer match, and increasing during the second half, may affect a number of potential aetiological factors for hamstring injury previously discussed. If the hamstring muscles become fatigued, both strength and flexibility of the unit may consequently be reduced (Agre, 1985). Kraus (1959) reported that fatigued muscles relax more slowly and less completely than non-fatigued muscles, resulting in physiological contracture (shortening of the musculo-tendinous unit). Therefore, injury may occur as a consequence of the associated loss of acute flexibility or strength (Kraus, 1959). Mair et al. (1996) furthermore observed reduced capacity of fatigued muscles to produce and absorb force before reaching the degree of stretch that causes injury. This may increase susceptibility to stretch injury in eccentric contractions, a common factor associated with hamstring strains (Stanton and Purdam, 1989; Hoskins and Pollard, 2005b).

As well as physiological changes within a muscle, coordination, technique or concentration may also be affected when fatigued, which may predispose a player to injury (Croisier,

2004). Specifically, coordination of muscular contraction within the same muscle affected by fatigue may be involved in increased susceptibility to injury. Due to the dual innervation of the biceps femoris, fatigue could lead to asynchrony in the activation of the separate parts of the muscle and result in inefficiencies (Croisier, 2004). Alternatively, proprioceptive acuity following fatigue could contribute to injury through deficient neuromuscular motor control and inappropriate muscular contraction (Hoskins and Pollard, 2005a). This may be observed as detrimental changes in technique, such as altered running technique following fatigue induced by repeated maximal sprints (Pinniger et al., 2000).

In order to investigate fatigue as an aetiological risk factor variable for injury in soccer, a form of aerobic fitness assessment is usually employed. In a prospective study following baseline assessment, Chomiak et al. (2000) identified poor physical condition to be a risk factor for all injuries, although specific injuries were not detailed. This finding supports the general agreement that lack of physical fitness is a risk factor for musculoskeletal injury (Neely, 1998). However, several studies have investigated this matter using military recruits rather than soccer players, or examined general injury risk factors as opposed to specific factors regarding hamstring strain injury. Additional research is therefore needed to substantiate and verify the claims of fatigue as a risk factor for hamstring strain injury, and investigate further its effects related to soccer-specific activities likely to evoke injury.

### **2.4.3. Summary**

The injury risk factors discussed include those that are modifiable: flexibility, muscle strength and imbalance, body mechanics and dysfunction, warm-up, inadequate rehabilitation and fatigue, and factors that are non-modifiable: age, previous injury and race. Although a number of potential risk factors have been proposed for hamstring strains,

there remains much to be understood about the aetiology of injury. Specifically, research should perhaps focus on factors which can be modified for injury prevention. In light of the factors discussed, fatigue may play a crucial role in the pathogenesis of hamstring injury by negatively affecting other aetiological modifiable risk factors. To date however, soccer-specific research into this area is sparse.

## **2.5. Fatigue, Sprinting and Hamstring Strain Injury Risk**

Sprinting is often reported as the primary mechanism for hamstring strain injuries in soccer (Hawkins et al., 2001; Árnason et al., 2004; Sheppard and Hodson, 2006). Woods et al. (2004) reported that 57% of hamstring strains in English soccer were sustained whilst sprinting, with 47% occurring during the last third of the first and second halves of matches. Therefore, it would seem logical to assume a relationship exists between fatigued sprinting and an increased risk of hamstring strain injury. Several aetiological risk factors have been previously reviewed relating to injury of the hamstring musculo-tendinous unit. These factors will be discussed in relation to fatigue and sprinting. However, in order to better understand how these risk factors may influence the mechanism of injury, the function of the hamstrings during sprinting will be initially discussed.

### **2.5.1. Hamstring Function in Sprinting**

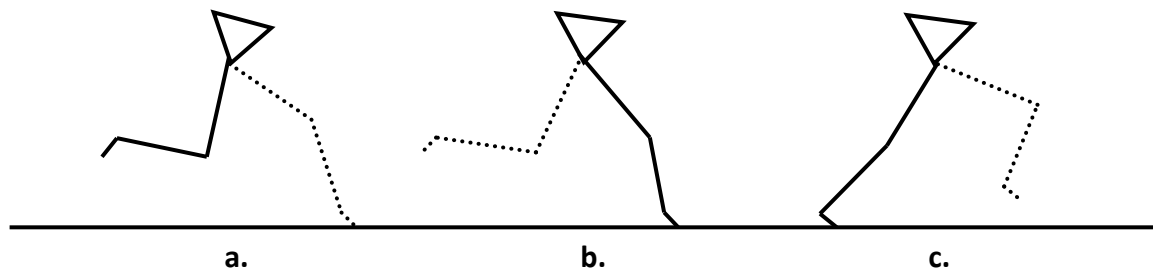
The role of the hamstring muscles during sprinting has been investigated by several authors (Sprague and Mann, 1983; Stanton and Purdam, 1989; Nummela et al., 1994; Pinniger et al., 2000). The gait cycle during sprinting lasts from toe-strike to toe-strike of the same dominant foot (Agre, 1985). During this cycle, the hamstring muscle group has been described by Stanton and Purdam (1989) as having three functions:

**1) Decelerating the thigh and lower leg prior to toe strike** (Figure 2.8.a). During the first half of the swing phase in the gait cycle, both the hip and knee rapidly flex. At this point, the knee flexes passively as a result of the rapid forward acceleration of the thigh caused by the hip flexion. Therefore, at this point the hamstring musculo-tendinous unit length remains essentially unchanged (Agre, 1985). The hamstring muscles then act eccentrically to decelerate the forward swing of the lower limb, previously initiated by the agonistic quadriceps muscle group (Petersen and Hölmich, 2005). This action prepares the limb for the stance phase to support the body, thus limiting the horizontal braking action. This causes the hamstrings to effectively store elastic energy which is recovered during the early stance phase (Stanton and Purdam, 1989).

**2) Stabilising the knee during the stance phase** (Figure 2.8.b). At early stance phase the hamstrings are elongated across both hip and knee joints. They concentrically contract to assist in producing hip extension proximally whilst also, and paradoxically, resisting knee extension distally by an eccentric muscle contraction (Agre, 1985). This combined action facilitates stability of the knee joint by preventing knee extension. As the hamstrings and quadriceps co-contract, they are able to absorb downward forces of the body weight through the stance leg and control knee flexion at toe strike and during the following period of flexion (Stanton and Purdam, 1989).

**3) Assisting in hip extension during the push-off phase** (Figure 2.8.c). In late stance phase, the hamstrings contract and assist the quadriceps to achieve push-off. They then continue to contract during the latter part of the stance phase to help protect the extending knee from hyperextension injury (Mann and Sprague, 1980).





**Figure 2.8.** Schematic representation of sprinting. Solid line = involved limb. Dotted line = uninvolved limb. a = Swing phase. b = early stance phase. c = late stance phase

## **2.5.2. Aetiological Risk Factors for Hamstring Injuries related to Sprinting and Soccer-specific Fatigue**

### **2.5.2.1. Flexibility and Range of Motion**

During sprinting, limited flexibility to the hamstring musculo-tendinous unit may cause it to be stretched beyond its ability to elongate during the latter part of the swing phase (Agre, 1985). This is most likely to transpire during sprinting, as opposed to other running speeds, as the flexibility requirement is at its greatest and the forces involved are at their maximum (Agre, 1985). Pinniger et al. (2000) investigated the effect of fatigue induced by repeated dynamic efforts on hamstring muscle function during sprinting. Results showed that subjects displayed significantly smaller thigh range of movement during sprinting in a fatigued condition. This was considered to indicate physiological shortening of the hamstring muscle fibres (Pinniger et al., 2000).

Alternatively, flexibility of the quadriceps muscle group may have implications regarding hamstring strain injury risk. Before initial contact during the sprint cycle, if the quadriceps muscles are tight, there may be increased passive elastic recoil of the tendon (Gabbe et al., 2005). This could cause increased forward acceleration of the lower limb, resulting in the leg being “whipped” through (Tupa et al., 1995). This action must be counteracted

eccentrically by the hamstrings, thus imposing a greater load on the muscles (Gabbe et al., 2005), and placing them on an increased stretch later in the cycle (Tupa et al., 1995). In relation to sprinting technique, decreased quadriceps flexibility may be observed as reduced knee flexion. During sprinting, Pinniger et al. (2000) observed decreased knee flexion after fatigue induced by repeated sprints. This finding was consistent with previous research (Sprague and Mann, 1983; Tupa et al. 1995) and proposed to increase hamstring injury risk.

The sprint cycle has also been investigated in relation to stride frequency, duration and length. Hanon et al. (2005) studied muscular fatigue on the kinematics and muscular function during sprinting. Results showed decreased stride length with fatigue, which supported the authors' hypotheses of mechanical adaptation related to fatigue of the biceps femoris and rectus femoris muscles. The findings supported previous work by Tupa et al. (1995) who reported reduced thigh and knee range of movement during fatigued sprinting. This may be explained as muscular physiological contracture, and thus may increase hamstring injury risk (Tupa et al., 1995). An alternative mechanism for hamstring injury is when the body is leaning forward, trying to maintain or increase running speed and overstriding occurs (Orchard, 2002). This technique alteration was observed by Williams and Cavanagh (1987) as an increase in stride length following fatigue. However, the study by Williams and Cavanagh (1987) analysed distance running as opposed to sprinting.

Overall, there remains ambiguity surrounding some of the hypotheses regarding flexibility and range of motion during sprinting. Furthermore, research appears contradictory as to whether fatigue induced increased or decreased stride length or flexibility of the hamstrings are risk factors for injury. Previous research has also failed to incorporate fatiguing protocols reflective of the demands of soccer, or utilised soccer players as subjects. This may have implications when extrapolating the results to soccer players, as sprinting at

slower speeds requires different muscle actions and amounts of activity (Mero and Komi, 1987). Hence, further investigation is required to explore the effect of soccer-specific fatigue on sprinting kinematics and stride parameters.

#### **2.5.2.2. Muscular Strength Deficiencies**

In the context of fatigue, the concept of strength in relation to injury risk may be divided into three categories for more specific examination: determination of peak strength, rate of force development, and muscle imbalances.

In terms of absolute strength, decreased hamstring force may cause reduced force absorption capabilities, therefore increasing the potential for injury (Garrett, 1996). Research using EMG has shown the hamstring muscles to generate reduced force during fatigued sprinting (Nummela et al., 1994; Pinniger et al., 2000). However, the studies did not incorporate a soccer-specific fatiguing protocol. During simulated soccer match-play, research has observed reduced hamstring peak torque due to fatigue (Rahnama et al., 2003; Greig, 2008). Gleeson et al. (1998) similarly examined the influence of a soccer-related fatiguing protocol on leg neuromuscular and musculoskeletal performance in recreational soccer players. Results showed that biceps femoris peak torque decreased progressively during the protocol, a significantly greater decline in strength when compared with that observed during a continuous treadmill run of equal duration and distance ( $P < 0.05$ ). Gleeson et al. (1998) suggested that the intermittent and multidirectional nature of soccer substantially increases physiological fatigue compared with other forms of exercise.

The rate of force development, or electromechanical delay (EMD), may also be associated with hamstring injury risk. During sprinting, the hamstrings alternate from functioning eccentrically to decelerate knee extension in the late swing phase, to concentrically to

become an active extensor of the hip joint (Woods et al., 2004). Verrall et al. (2001) proposed that this rapid changeover from eccentric to concentric function is when the hamstrings are most vulnerable to injury. This may be displayed as a decreased rate of force development (or increased EMD) during the changeover of contraction types. Research analysing the effect of fatigue on EMD of the hamstring muscles during sprinting is currently scarce. However, in the aforementioned study by Gleeson et al. (1998), EMD of the biceps femoris was significantly increased following the protocol compared with pre-exercise values ( $P < 0.05$ ). Although this was related to greater risk of threatening the integrity of the ACL, it may also have implications for increased risk of hamstring strain injury. However, additional research is needed to explore this area further.

Muscle imbalances between the hamstrings and quadriceps have been proposed as a risk factor for hamstring injury (Dauty et al., 2003). This muscular imbalance was investigated by Andrews et al, (2005) in regard to the effect of fatigue induced by repeated sprints. After a standardised warm-up, ARF players immediately performed either: three maximal concentric and eccentric hamstrings and quadriceps actions on an isokinetic dynamometer, or performed 6 x 40 m maximal effort sprints (the fatigued condition) before completing the same dynamometry routine. Results showed an 8% performance decrement across the 6 x 40 m sprints, thereby indicating the task was successful in producing fatigue. The isokinetic dynamometry results revealed a reduction in the functional H:Q ratio with fatigue. Therefore, repeated bouts of sprints, as occurs regularly during soccer, may alter the muscular imbalance to place the hamstrings at an increased risk of injury.

The H:Q ratio has also been investigated regarding the effect of soccer-specific fatigue. Rahnama et al. (2003) investigated the effect of fatigue simulating the work rate of soccer match-play on the H:Q strength ratios in amateur soccer players. Results showed that the

functional H:Q ratio; ideally 1.0 (indicating low injury risk), decreased progressively from 0.77 pre-exercise to 0.67 post-exercise. This finding was more recently supported by Greig (2008) although using a more intermittent 90 min soccer-specific treadmill protocol. The muscular imbalance observed with fatigue may imply that the hamstrings have insufficient strength to counteract the force produced by the quadriceps. This may consequently result in eccentric overload, and thus cause tearing of the hamstring musculo-tendinous unit (Garrett, 1990). However, the fatiguing protocols employed by Rahnama et al. (2003) and Greig (2008) were performed on motorised treadmills. This equipment inhibits utility movements or the self-performed acceleration and deceleration as are inherent in soccer. These movement demands may be crucial for replicating the physiological and local muscular fatigue of soccer (Bangsbo, 1994a). Therefore, the findings may not be truly reflective of the fatigue associated with soccer match-play.

### **2.5.2.3. De-synergic Contraction**

The dual innervation of the two heads of the biceps femoris has been suggested as a risk factor for hamstring injury (Verrall et al., 2001). Fatigue inhibiting coordinated activation of the separate parts of the biceps femoris may result in inefficiencies that increase injury risk (Croisier, 2004). However, research is yet to examine the timing of activation of the separate parts of the biceps femoris muscle, and also in relation to soccer-specific fatigue.

Asynchrony in the timing and peak force of the three separate hamstring muscles may also be related to increased hamstring injury risk. Jönhagen et al. (1996) investigated the timing and amplitude of the hamstring muscles during fatigued sprinting. Results showed lower total peak force of the biceps femoris than of the medial hamstrings with fatigue. Research has furthermore observed significantly increased EMG activity of the biceps femoris during

fatigued sprinting (Nummela et al., 1994) and greater peak EMG throughout the progression of a 90 min soccer simulation (Greig et al., 2006). However, both studies failed to concurrently examine muscle activity from the medial hamstrings. Nevertheless, the activity patterns from the biceps femoris demonstrating increased effort to maintain running speed (Nummela et al., 1994) and accommodate changes in speed (Greig et al., 2006) may imply increased risk of injury. Currently, these theories remain speculative until additional scientific support and enhanced technology is available.

#### **2.5.2.4. Body Mechanics**

A potential mechanism for hamstring injury when sprinting is when the body increases its forward lean to maintain or gain additional speed (Orchard, 2002). This causes increased lumbar lordosis and anterior pelvic tilt, which, due to the bi-articular nature of the hamstrings may predispose the muscle group to injury by increasing its relative length (Hoskins and Pollard, 2005b). Fatigued sprinting has been associated with increased forward lean and over-striding (Orchard, 2002). Therefore, the relationship between body mechanic alterations during fatigued sprinting and increased risk of hamstring injury would seem logical. However, this relationship has received little research investigation, particularly in soccer players. Few experimental studies have attempted to analyse body mechanics during specific functional movements such as sprinting, and in relation to fatigue. Watson (1995) accounted this to the difficulty in reliably assessing defects of body mechanics. However, modern day advances in technology may suggest there is greater potential for investigation into this area. This could be vital for gaining a greater insight into the association between the effects of soccer-specific fatigue on body mechanics during sprinting and hamstring injury risk.

### **2.5.3. Summary**

Research has investigated the effects of fatigue on the mechanics of sprinting. This has provided some understanding of the aetiological risk factors for hamstring strains and their association with the sprinting injury mechanism. However, many of the fatiguing protocols employed by previous research have not reflected the nature or demands of soccer match-play. Hence, the transferability of the findings to the subject population under review remains questionable. Further investigation is required using more accurate soccer simulations to gain a better insight into the role of fatigue in the biomechanics of sprinting. This knowledge may enable more effective intervention strategies for hamstring strains to be developed to reduce the risk of injury.

### **2.6. Fatigue and Soccer Match-play: Physiological Response and Activity Profile**

Soccer is an intermittent activity involving high and low-intensity exercise during match-play, thus requiring players to be competent in aerobic and anaerobic power (Stølen et al., 2005). To be played at a high level, players must be able to perform at speeds comparable to those of a sprint track athlete, yet also have the muscle stamina to endure an entire 90 min game whilst superimposing jumping, tackling, rapid changes of direction and kicking (Robinson and White, 2005). These actions are affected by the intensity at which they are performed, distance they cover and also frequency at which they occur, all of which are irregular in nature (Reilly, 1997). Reilly (2005) proposed that the physiological responses to soccer can highlight the extent to which players can impose demands on themselves, and also provide an indication as to when they are underperforming by failing to meet the requirements of the game. Such information is commonly attained via motion analysis and can be used to design fitness and injury prevention strategies (Reilly, 1996).

Soccer performance depends upon a myriad of factors including technical, tactical, physical, physiological and mental areas (Stølen et al., 2005) and fatigue is a complex interaction of these processes (Aaronson et al., 1999). A physiological perspective would suggest that fatigue is defined as failure to maintain the required or expected force (Edwards, 1981), whereas from a local muscular perspective, fatigue may be defined as the inability to sustain a required contraction level due to failure of the excitation-contraction coupling mechanism (Gandevia et al., 1995). This review will focus on the physiological and local muscular fatigue associated with soccer match-play, giving an overview of the important literature of soccer physiology and work-rate.

### **2.6.1. Work-rate of Soccer with Reference to Fatigue**

Exercise intensity during soccer matches is commonly measured using the overall distance covered by each player (Reilly, 1996). This measure of work-rate represents a compilation of discrete actions or movements during matches, and can be further classified according to the type of action or movement, intensity, duration, and frequency (Reilly, 1997).

Motion analysis of professional soccer players was first investigated by Reilly and Thomas (1976), with numerous studies subsequently conducted (Bangsbo et al., 1991; Drust et al., 1998; Thatcher and Batterham, 2004). On average, outfield players cover 8-12 km during a game, with midfielders covering the greatest distance per match (Reilly, 1996). However, for high-level players the distance covered may be more in the order of 10-12 km (Stølen et al., 2005), with studies reporting professional players covering greater distances than non-professionals (Ekblom, 1986; Mohr et al., 2003). This may be due to greater aerobic fitness and increased capacity to sustain high fractional utilisation of aerobic power by elite players (Shephard, 1999). In general, distance covered in matches has changed over the

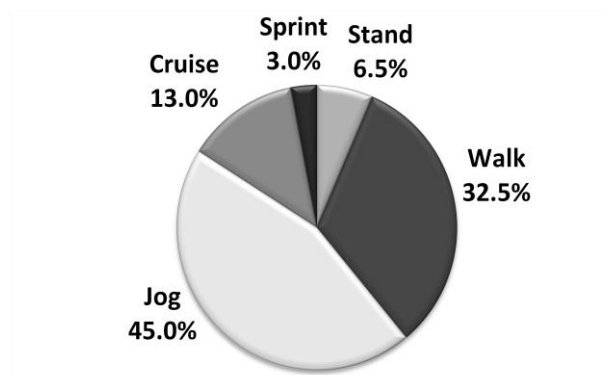


years, with the contemporary game of high-level soccer becoming increasingly demanding. Strudwick and Reilly (2001) compared work-rates of English Premier League players over two seasons (1998-1999 and 1999-2000) with previous observations of top English League players prior to 1992. Results revealed that contemporary players covered ~1.5 km further in a match than their earlier counterparts. Even though alternate methodologies and technologies were utilised to record match work-rates in the respective studies, this finding substantiates work by Williams et al. (1999) who reported a faster tempo to matches in more recent times. This may be due to rule changes, such as prohibiting the back-pass, penalising time-wasting and permission to use three substitutes (Reilly, 2005).

During matches it is widely accepted that distance covered is reduced during the second half by 5-10% (Reilly and Thomas, 1976; Withers et al., 1982; Bangsbo et al., 1991; Mohr et al., 2003). This finding appears to be consistent within the literature regardless of playing standard, age of match-play data acquisition or methods of data collection. The manifestation of fatigue observed is most pronounced in centre-backs and strikers, and less apparent for midfielders and full-backs who tend to have higher levels of aerobic fitness to sustain their work-rate (Reilly, 2005).

Reflective of contemporary soccer, the total distance covered encompasses over 1250 short, different activities (Mohr et al. 2003), with a change in type or intensity of activity occurring approximately every six seconds. The activities performed which make up overall distance covered are: standing ( $<0.5 \text{ km}\cdot\text{h}^{-1}$ ; 6.5%), walking ( $5 \text{ km}\cdot\text{h}^{-1}$ ; 32.5%), jogging ( $10 \text{ km}\cdot\text{h}^{-1}$ ; 45%), cruising/striding ( $17 \text{ km}\cdot\text{h}^{-1}$ ; 13%) and sprinting ( $>23 \text{ km}\cdot\text{h}^{-1}$ ; 3%; Thatcher and Batterham, 2004; Figure 2.9). Utility movements involving backwards or sideways actions contribute 36.9% of total movement (Thatcher and Batterham, 2004). Activities are performed almost continuously, with only 43.4 static rest pauses of three

seconds duration on average every two minutes, and with approximately less than 2% of the total distance covered in possession of the ball (Reilly, 1997).



**Figure 2.9.** Relative distances covered in different categories of activity for outfield players during soccer match play (created using data from Thatcher and Batterham, 2004)

The amount of deceleration actions have also been measured during matches, with 496 movements recorded during high-level English soccer (Bloomfield et al., 2008). This has been postulated to further increase the eccentric stresses placed on muscles which may be an important factor for injury risk (Woods et al., 2004). The high proportion of utility movements and deceleration actions should therefore be considered by researchers when attempting to simulate match demands, particularly those investigating injuries in soccer.

An alternative method of measuring work-rate during matches is by analysing movement intensity. Low intensity activity is performed walking and jogging ( $<10\text{km}\cdot\text{h}^{-1}$ ) whilst high intensity is performed running/cruising and sprinting ( $>10\text{km}\cdot\text{h}^{-1}$ ). Approximately 80% of activity is performed at low-intensity, with high-intensity accounting for only ~16% of total time, and the remaining game comprising of static pauses (Thatcher and Batterham, 2004). The amount of sprinting and high-speed running is lower during the second half of matches (Bangsbo et al., 1991; Bangsbo, 1994a; Mohr et al., 2003), with high-speed running in particular significantly reduced ( $P < 0.05$ ) during the final 15 min of games (Mohr et al.,

2003). Consequently, low-intensity activity and rest periods increase towards the end of a match when players cannot maintain their running to support team mates (Reilly, 2005).

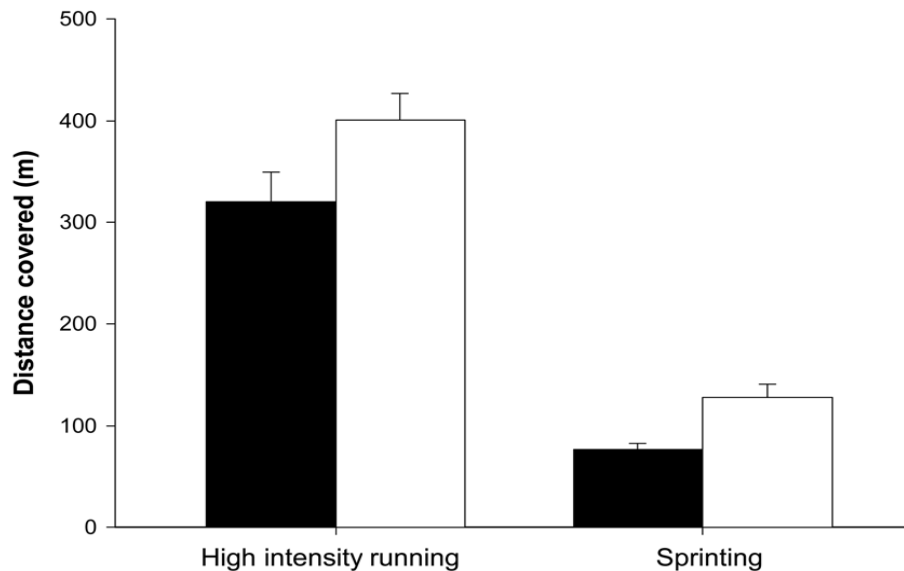
In conjunction with general fatigue, a phenomenon known as “temporary fatigue” has also been suggested (Mohr et al., 2003) as a factor affecting performance. Research using computerised time-motion analysis of elite male soccer players has observed that the five minutes following the most intense period of the match results in reduced high-intensity running to below that of the match average (Mohr et al., 2003). Although this may have been the result of the natural variation in game intensity due to tactical or psychological factors, it was attributed to temporary fatigue by Mohr et al. (2003).

### **2.6.2. Sprinting and Soccer Match-play with Reference to Fatigue**

The ability to produce high rates of power output and sprint at high velocity is essential to soccer performance and considered critical to the outcome of the game (Wragg et al., 2000). Sprinting constitutes around 3% of total distance covered during a match (Thatcher and Batterham, 2004), occurring approximately once every 90 s and lasting an average 2-4 s (Bangsbo et al., 1991). Players commonly sprint over 10-30 m (Bangsbo et al., 1991a), with sprints over 30 m demanding markedly longer time to recover than for average sprints of 10-15 m (Bangsbo and Mohr, 2005). Sprint speed during top-class matches has been observed to reach peak values of  $9 \text{ m}\cdot\text{s}^{-1}$ , with values somewhat higher in attackers and defenders than goalkeepers and midfield players (Luhtanen, 1994).

As previously mentioned, the amount of high-intensity activity is reduced during the second halves of soccer matches (Bangsbo; Mohr et al., 2003). In addition, it has been observed that substitutes who have come on during the second half sprint and run at a

higher intensity (25% greater) than players who have completed the entire game (Mohr et al., 2003), particularly during the final 15 min (Figure 2.10).



**Figure 2.10.** High-intensity running and sprinting during the final 15 min of a game (taken from Mohr et al., 2003). Players participating in the entire game (■) Substitutes only participating in the second half (□)

Computerised time-motion analysis of soccer match-play has identified a fatigue effect on sprint ability. Performance has been assessed by means of a repeated sprint test conducted immediately before and after each half of a match (Mohr et al., 2004). Findings revealed impaired sprinting performance post-exercise by 2% compared with before the match which was attributed to depleted glycogen levels (Mohr et al., 2004). Krstrup et al. (2003) alternatively investigated sprint performance during soccer match-play with respect to the temporary fatigue theory. Players performed a repeated sprint test immediately after a short intense period during a match and also at the ends of each half. Results showed that, following intense periods during the first half, players' sprint performance was significantly reduced ( $P < 0.05$ ). However, performance had recovered by the end of the first half to pre-exercise values, thus suggesting temporary fatigue was experienced by players (Krstrup et al., 2003).

### 2.6.3. Fatigue and the Physiological Response to Soccer Match-play

There have been several attempts to determine the aerobic contribution of soccer match-play by measuring oxygen uptake ( $\text{VO}_2$ ). However, it has been claimed that none seem to be successful in obtaining realistic values (Bangsbo, 1994a). The major problem is that determining  $\text{VO}_2$  within the game interferes with normal match-play, therefore, only minor parts of a match have been analysed (Bangsbo, 1994a). Alternatively, heart rate has been shown to provide a useful index of overall physiological strain with an average of  $165 \text{ b}\cdot\text{min}^{-1}$  observed in high-level soccer (Table 2.1).

**Table 2.1.** Heart rate of male soccer players

| Study                 | Level/Country      | Subject # | Type of Match | HR $\text{b}\cdot\text{min}^{-1}$   |
|-----------------------|--------------------|-----------|---------------|-------------------------------------|
| Edwards & Clark, 2006 | Semi-pro (Eng)     | 8         | Friendly      | 156                                 |
| Bachev et al., 2005   | Elite Junior (Bul) | 16        | Friendly      | 156                                 |
| Mohr et al., 2004     | Div 4 (Den)        | 9         | Friendly      | 160                                 |
|                       | Div 4 (Den)        | 16        | Friendly      | 162                                 |
| Stroyer et al., 2004  | Elite 12yr (Den)   | 7         | League        | 175                                 |
|                       | Elite 12yr (Den)   | 7         | League        | 176                                 |
| Ali & Farrally, 1999  | Semi-pro (Scot)    | 9         | League        | 172                                 |
|                       | Uni (Scot)         | 9         | League        | 167                                 |
| Ogushi et al., 1993   | Semi-pro (Jap)     | 2         | Friendly      | 162                                 |
| Bangsbo et al., 1991  | Div 1/2 (Den)      | 6         | League        | 159                                 |
| Van Gool et al., 1988 | Uni (Bel)          | 7         | Friendly      | 167                                 |
| Reilly, 1986          | League (Eng)       | -         | Friendly      | 157                                 |
| Agnevik, 1970         | Div 1 (Swe)        | 1         | League        | 175                                 |
|                       |                    |           |               | <b>Mean: <math>165 \pm 8</math></b> |

The average heart rate observed during soccer matches corresponds to a relative metabolic loading of approximately 75%  $\text{VO}_{2\text{max}}$  (Reilly, 1997). This value is close to the lactate threshold (80-90%  $\text{VO}_{2\text{max}}$ ) which would be physiologically unachievable to maintain over a long period of time due to accumulation of blood lactate (Hoff, 2005). The resultant energy expended for a player of 75 kg body mass is 70 kJ per min. This is greater than the energy requirements of locomotion over 11 km (typically observed during a match) and may be attributed to the extra energetic demands associated with soccer activities, including jumping, accelerating, decelerating, tackling and so forth (Reilly, 1997).

The circulatory strain experienced by players during match-play appears to remain relatively high (Bangsbo, 1994a). This may be due to the short (~3 s) but frequent recovery periods during match-play (Reilly, 1997). Despite this, there are large inter-individual differences in the aerobic energy production during a match. Again, this may be due to a variety of potential influencing factors such as player motivation, physical capacity, tactical limitations and team position (Bangsbo, 1994b).

Along with circulatory strain, concentration of lactate in the blood can also be used to assess physiological fatigue during matches as an indicator of anaerobic energy production (Bangsbo, 1994a). A large production of lactate during intense exercise is associated with elevated acidity within the exercising muscles (Bangsbo, 2000). This may affect functioning of the muscle cells and impair performance (Bangsbo, 2000). Therefore, fatigue during soccer match-play, resulting in lactate accumulation within skeletal muscles, may impair technical ability (Hoff, 2005).

To measure the level of lactate in the blood, the most widely used strategy of attaining blood samples for analysis is to obtain the samples at half-time and again at the end of play,

as logistically it would be impossible to record the information continuously. Mean blood lactate concentrations of 2-10 mmol·L<sup>-1</sup> have been observed during games, with individual values above 12 mmol·L<sup>-1</sup> also recorded (Ekblom, 1986). Such high peak values would be unfeasible to sustain throughout a game, but instead may reflect the intermittent nature of the sport and accumulation of lactate after a prolonged period of high-intensity activity.

Krustrup et al. (2006) examined blood and muscle metabolites during soccer matches in relation to sprint performance. Despite fluctuations in blood lactate during the game, there was no significant difference observed between first and second half values (6.0 vs 5.0 mmol·L<sup>-1</sup>;  $P > 0.05$ ). Additionally, no relationship was found between decreased sprint performance and any of the blood metabolites measured. However, earlier findings by Bangsbo et al. (1991) reported a significantly higher mean blood lactate concentration during the first than second half of elite matches (4.9 mmol·L<sup>-1</sup> vs 3.7 mmol·L<sup>-1</sup>;  $P < 0.05$ ). The divergence in findings between studies may be explained by the difficulty and logistics in obtaining blood samples, possibly an artefact of the timing of samples with respect to the type and intensity of activity conducted prior to assessment (Reilly, 1997).

Evidence suggests that overall energy yield from anaerobic metabolism during a game is slight (Reilly, 1997). This would seem logical as the total amount of high-intensity exercise during soccer accounts for only ~16% of total game time (Thatcher and Batterham, 2004). Instead, it may play a more significant role in terms of temporary fatigue during a game, whereby excessive proton (H<sup>+</sup>) production may impair muscle performance during intense contractions. This was reported by Krustrup et al. (2003) who observed reduced sprint performance temporarily after an intense period of play during a soccer match.

Soccer is a high-intensity, intermittent sport suggesting carbohydrate as a primary energy source, with muscle glycogen potentially the most important substrate for the exercising muscles (Reilly, 2000). Muscle glycogen depletion may therefore be an important mechanism behind reduced performance at the end matches. Consequently, performance may be enhanced by an initial boosting of muscle glycogen reserves (Bangsbo et al., 1992).

To elucidate the role of muscle glycogen in soccer, muscle biopsies have been collected before, at half-time and after a match for analysis of glycogen content. Saltin (1973) found that glycogen stores were almost depleted at half-time when pre-match values were low ( $\sim 200 \text{ mmol}\cdot\text{kg dry weight}^{-1}$ ), and experimental players covered 25% less distance than control players. For players who started the game with normal muscle glycogen concentrations ( $\sim 400 \text{ mmol}\cdot\text{kg dry weight}^{-1}$ ), values remained high at half-time but were below  $\sim 50 \text{ mmol}\cdot\text{kg dry weight}^{-1}$  at the end of the game. This glycogen depletion could be implicated in the 5-10% decrease in distance covered during the second halves of matches (Reilly and Thomas, 1976; Withers et al., 1982; Bangsbo et al., 1991; Mohr et al., 2003). However, Krstrup et al. (2006) reported concentrations of  $\sim 200 \text{ mmol}\cdot\text{kg dry weight}^{-1}$  after a match, indicating that muscle glycogen stores are not always depleted during matches. This divergence in findings could be attributed to the varying glycogen levels from different muscles and muscle fibre types or perhaps the variability of the muscle biopsy method (Lexell et al., 1985). Regarding muscle fibre type glycogen depletion, Krstrup et al. (2000) obtained and analysed muscle tissues before and after a match for fibre type specific glycogen depletion. Findings showed a significant reduction in muscle glycogen of type IIA fibres after the match (Krstrup et al., 2003). Therefore, it could be hypothesised that thigh muscles, such as the hamstrings, which contain a high proportion of



type II muscle fibres (Hoskins and Pollard, 2005a) may be at increased risk of fatigue due to glycogen depletion towards the end of matches.

Depleted muscle glycogen during soccer may also influence the type of activity performed and, more specifically, the speed of running. Saltin (1973) observed players with lower initial glycogen levels not only covered 50% less distance than control players, but also covered 50% of the distance walking and only 15% at maximal speed sprinting. This was compared with 27% distance covered walking and 24% covered sprinting for control players. Furthermore, Krstrup et al. (2006) reported a reduction in sprint performance in progression of a soccer match in concurrence with depleted muscle glycogen levels of type II muscle fibres. Therefore, glycogen depletion and the associated fatigue appears to inhibit maximal effort sprints during soccer match-play (Krstrup et al., 2006).

Additional factors have been proposed, such as dehydration and hyperthermia, as agents responsible for the development of fatigue in the latter stages of soccer matches (Reilly, 1997). During a typical match played in a normal thermal environment, average core body temperatures ranges from 39.0 to 39.5 °C (Mohr et al., 2004). At these temperatures players can lose more than three litres of body fluid (Bangsbo, 1994a; Reilly, 1997). The resultant loss in body mass of just 1-2% due to dehydration may contribute to an elevated core temperature and cardiovascular strain (Hoffman et al., 1994). This can impair performance (Saltin, 1964) and perhaps increase risk of injury towards the end of matches.

#### **2.6.4. Summary**

Fatigue appears evident as soccer matches progress, resulting in reduced distance covered and lower activity intensity. In regard to sprinting, not only does the number of sprints decrease towards the end of a match whilst fatigued, but the intensity at which they are

performed is also reduced. This impairment in sprint performance, and perhaps technique, could play a crucial role in increasing susceptibility to hamstring strain injury often sustained towards the end of matches and whilst sprinting (Woods et al., 2004).

There have been many factors investigated in association with fatigue development during soccer matches, both towards the end of a game and temporarily during it. These include: heart rate and percentage of heart rate maximum, blood lactate, muscle glycogen and fluid loss. Examination of these various factors may therefore be useful when attempting to validate soccer match-play simulations.

### **2.7. Simulating Soccer-specific Fatigue during Match-play**

The physiological demands of soccer require players to be competent in several aspects of fitness, including aerobic and anaerobic power, muscle strength, flexibility and agility (Reilly and Thomas, 1976). These factors interact to characterise the intermittent nature and intensity of soccer. Researchers in sport and exercise science have been discouraged in their attempts to study soccer due to the lack of available experimental models (Reilly, 1990) especially regarding match-play fatigue. As a consequence, researchers have devised laboratory-based simulations to assess the physiological and metabolic responses to soccer match-play.

Simulations have been developed to recreate the work load of soccer matches (Gleeson et al., 1998; Drust et al., 2000a; Nicholas et al., 2000; Thatcher and Batterham, 2004; Greig et al., 2006). These simulations have been used to analyse the physiological and mechanical demands of the activity or as training tools to provide individual profiles of players' respective strengths and weaknesses. This data has also been used to form the basis to develop optimal training and injury prevention strategies (Svensson and Drust, 2005). The

ability to assess these simulations is vital for interpreting the validity of the study findings, and enabling informed judgements as to their accuracy in replicating soccer match-play demands. The creation of a valid simulation is crucial for investigating the effect of soccer-specific fatigue on injury risk factors, such as altered sprinting technique or muscular strength and imbalances regarding hamstring strains.

Previous research that has attempted to develop soccer simulations can be broadly split into two main categories: 1) those recreating the activity profile using a treadmill, or 2) a free-running protocol utilising repetitive intermittent shuttle running.

### **2.7.1. Treadmill Simulations**

The first motorised, treadmill-based soccer-specific intermittent simulation was created by Drust et al. (2000a). The total duration of the protocol represented one half of a match: 46.11 min (Table 2.2), with each half subdivided into two 22.4 min activity cycles. Each cycle consisted of 23 discrete bouts of activity: six bouts of walking, six bouts of jogging, three cruises and eight sprints; the order of which was devised to replicate the non-cyclical nature of soccer. The duration of each bout was determined by matching the percentage of total time for each movement category during match-play to that based on data by Reilly and Thomas (1976); walking 35.3 s, jogging 50.3 s, cruising 51.4 s and sprinting 10.5 s. The speed of each activity was based on soccer match-play observations by Van Gool et al. (1988).

**Table 2.2.** 45 min activity profile presented from protocol by Drust et al. (2000a)

| Type of Activity | Number of Activities | Mean Duration (s) | Speed (km·h <sup>-1</sup> ) |
|------------------|----------------------|-------------------|-----------------------------|
| Walk             | 24                   | 35.3              | 6                           |
| Jog              | 24                   | 50.3              | 12                          |
| Cruise           | 12                   | 51.4              | 15                          |
| Sprint           | 32                   | 10.5              | 21                          |
| <b>Total</b>     | <b>92</b>            | -                 | -                           |

Drust et al. (2000a) compared the physiological responses: heart rate, minute ventilation, oxygen consumption, sweat rate and rectal temperature, during the exercise protocol with those during steady-state exercise at the same average intensity (12 km·h<sup>-1</sup>) for an identical time period. The results showed an energy expenditure of 68% VO<sub>2max</sub> during the intermittent protocol which was claimed by the authors as similar to the 70-75% VO<sub>2max</sub> observed by Reilly (1990) during actual matches. Furthermore, the heart rate recorded was also found to be similar to match-play responses observed by van Gool et al. (1983).

Aside from the physiological responses observed, it was concluded that the intermittent protocol replicated soccer match-play in terms of total duration (46:11 min per half), activity pattern (jogging, sprinting, cruising, walking) and the speeds, as it was based on previous research (Van Gool et al., 1988). Regarding limitations, the authors did acknowledge the omission of utility movements, however, there may be more important limitations to consider. The protocol included only 92 discrete bouts of activity, compared with over 1250 activities observed during match-play (Mohr et al. 2003). Consequently, the actual duration spent performing each movement intensity was substantially longer than performed during matches. Of this, just over 50% of total distance was covered at high-intensity cruising or sprinting, again, considerably greater than ~16% performed in matches

(Thatcher and Batterham, 2004). Finally, players completed a total distance in excess of 18 km, much greater than the 10-12 km completed on average in matches (Stølen et al., 2005). Therefore, although the protocol may have replicated the physiological fatigue of match-play, it may not reflect the activity profile of soccer and thus local muscular fatigue, which could alter the biomechanics of movement to effect injury risk.

In reflection of their earlier findings and limitations, Drust et al. (2000b) amended their protocol to incorporate a greater number of changes in activity, increasing the frequency to 198 over the 90 min. Furthermore, the protocol was performed on a non-motorised treadmill, therefore allowing significantly faster acceleration and deceleration (Drust et al., 2000b). This modification ensued greater time periods at each exercise intensity, therefore reducing the uncertainty of interpreting the physiological responses associated with non-uniform intensities (Drust et al., 2007). The equipment also allows individuals to reach maximal sprinting speeds, thereby enabling evaluations to the associated power efforts to be recorded (Drust et al., 2007). The redeveloped protocol by Drust et al. (2000b) was based on more contemporary match-play motion analysis data obtained in an observational study using South American international players (Drust et al., 1998). However, as high-level English players cover a mean distance per match of  $10.10 \pm 0.70$  km compared with  $8.64 \pm 1.16$  km by the South American players (Drust et al., 1998), the applicability of the protocol to English players is questionable.

In order for a simulation to be deemed a truly valid indication of soccer match-play, the same subject population should be examined under both conditions of actual match-play and simulation. At present, Thatcher and Batterham (2004) have completed the only study using this approach, attempting a direct validation of their sport-specific intermittent treadmill protocol (SSEP). Motion characteristics of 12 first team and 12 scholars (under

19's) from an English Premiership club were observed using camcorders. The videotapes were replayed to a television monitor where the activity, stride number and specific player positioning on the pitch were transferred to a micro-computer. The data were then analysed to develop the SSEP for a non-motorised treadmill, with the activity profile involving two bouts of 9x5-min repeating cycles separated by a 15 min rest period (half-time). The protocol utilised five movement intensities: standing ( $0 \text{ km}\cdot\text{h}^{-1}$ ); walking ( $5 \text{ km}\cdot\text{h}^{-1}$ ); jogging ( $10 \text{ km}\cdot\text{h}^{-1}$ ); running ( $17 \text{ km}\cdot\text{h}^{-1}$ ); and sprinting ( $>23 \text{ km}\cdot\text{h}^{-1}$ ), with a change in activity every 10-20 s equalling approximately 360 changes during the 90 min.

The protocol was validated using six male soccer players who completed both the SSEP and a separate soccer match. Heart rates were recorded throughout both testing sessions, and capillary blood and expired air were taken at rest and at 15 min intervals throughout the SSEP trial. Results showed a mean heart rate response of  $166 \pm 9 \text{ b}\cdot\text{min}^{-1}$  for match-play and  $166 \pm 12 \text{ b}\cdot\text{min}^{-1}$  for the SSEP protocol. The mean response for  $\text{VO}_{2\text{max}}$  during the SSEP was  $70 \pm 3\%$ , and mean blood lactate concentrations for the first and second halves of  $5.37 \pm 1.15$  and  $4.74 \pm 1.25 \text{ mmol}\cdot\text{L}^{-1}$  respectively. The authors concluded that heart rate between the two conditions demonstrated good comparability, and that oxygen uptake data and blood lactate concentration values recorded during the SSEP were comparable to match-play observations (Smaros, 1980). Therefore, it was suggested by the authors that the SSEP provided an accurate approximation of the stresses of soccer match-play (Thatcher and Batterham, 2004).

However, the activity profile of the SSEP included only approximately 360 discrete bouts of activity during the 90 min. Therefore, as for the protocols by Drust et al. (2000a and 2000b), significantly longer periods of time were spent performing individual movement bouts. In the high-intensity activities (running and sprinting which formed ~22% of the

total distance covered), this may have exacerbated the fatigue response to substitute for the lack of utility movements shown to be an important determinant of the physiological requirements of soccer-specific exercise (Bangsbo, 1994).

In order to advance the knowledge within this area, Greig et al. (2006) designed a more recent soccer-specific, intermittent treadmill protocol based on notational analysis of match-play (Bangsbo, 1994b). Greig et al. (2006) attempted to more accurately recreate the activity pattern of match-play by increasing both the number and frequency of activities while reducing their duration. The match-play data was used by Greig et al. (2006) to create a 15 min activity period (Table 2.3) which was repeated six times in total over the 90 min.

**Table 2.3.** 15 min activity Profile presented from Greig et al. (2006)

| <b>Type of Activity</b> | <b>Number of Activities</b> | <b>Mean Duration (s)</b> | <b>Speed (km·h<sup>-1</sup>)</b> |
|-------------------------|-----------------------------|--------------------------|----------------------------------|
| Stand                   | 20                          | 7.8                      | 0                                |
| Walk                    | 55                          | 6.7                      | 4                                |
| Jog                     | 42                          | 3.5                      | 8                                |
| Low Speed               | 46                          | 3.5                      | 12                               |
| Moderate Speed          | 20                          | 2.5                      | 16                               |
| High Speed              | 9                           | 2.1                      | 21                               |
| Sprint                  | 3                           | 2.0                      | 25                               |
| <b>Total</b>            | <b>195</b>                  | -                        | -                                |

Considering the activity profile previously discussed, the protocol by Greig et al. (2006) appears to more closely replicate the activity pattern of match-play than previous efforts (Drust et al., 2000a; 2000b; Thatcher and Batterham, 2004). To validate the protocol, the physiological and mechanical fatigue responses were compared with a steady-state 90 min

run at a constant speed of  $6.5 \text{ km}\cdot\text{h}^{-1}$  to provide an equivalent total distance of 9.72 km (Greig et al., 2006). Ten semi-professional soccer players performed each protocol on separate occasions with heart rate (monitored every five seconds) and blood lactate (determined at rest and at the end of each 15 min exercise period) used to analyse the physiological response (Greig et al., 2006). The intermittent treadmill protocol produced a greater physiological response than the steady-state protocol at  $6.5 \text{ km}\cdot\text{h}^{-1}$  (Greig et al., 2006), but failed to reach the magnitude of responses observed during actual match-play. The mean heart rate for the first 15 min during the intermittent protocol was  $125 \text{ b}\cdot\text{min}^{-1}$  which only increased to  $135 \text{ b}\cdot\text{min}^{-1}$  during the final 15 min (Greig et al., 2006). This is substantially lower than the  $171 \text{ b}\cdot\text{min}^{-1}$  observed in competitive matches (Bangsbo, 1994a). Similarly, blood lactate values peaked at  $1.4 \text{ mmol}\cdot\text{L}^{-1}$  (Greig et al., 2006), whereas concentrations of  $4.4 \text{ mmol}\cdot\text{L}^{-1}$  have been recorded at the end of matches (Bangsbo et al., 1991a). The lower physiological responses observed by Greig et al. (2006) compared with those recorded during match-play (Bangsbo, 1994a) were attributed to differences in situational factors and the lower emotional stress experienced when testing in a laboratory as opposed to in a competitive environment (Whitehead et al., 1996).

Despite the lower physiological stress observed by Greig et al. (2006), it was argued that the mechanical fatigue induced by the intermittent protocol would be greater due to the more frequent periods of acceleration and deceleration. Furthermore, this may have greater implications for injury risk at the end of matches (Greig et al., 2006). However, by using a motorised treadmill, the muscular force and energy required to accelerate and decelerate between activity intensities is not necessarily produced by the working muscles, but automatically by the treadmill. Therefore, questions may also be raised as to the ability of the protocol to induce the local muscular fatigue reflective of match-play.



At present, although the protocols reviewed (Drust et al., 2000a and 2000b; Thatcher and Batterham, 2004; Greig et al., 2006) are commonly utilised to induce soccer-specific fatigue, their ability to recreate both physiological and mechanical fatigue whilst reflecting the nature of soccer remains questionable. However, whether any form of treadmill protocol is able to recreate soccer-specific fatigue due to the absence of utility movements crucial in soccer and affecting the physiological responses still remains to be demonstrated.

### **2.7.2. Free-running Protocols**

Soccer-specific free-running tests are very popular amongst coaches due to their simplicity and minimal use of equipment (Mirkov et al., 2008). Within research, free-running tests also have the advantage of enhanced specificity of evaluation, therefore increasing the test validity (Balsom, 1994). However, there is a general lack of data confirming their reliability, particularly regarding the tests of anaerobic performance (Mirkov et al. 2008).

One of the earliest created soccer-specific free-running tests was the prolonged high intensity intermittent shuttle run (PHISR), designed to closely simulate match-play (Gleeson et al., 1998). The PHISR was assessed by monitoring players' heart rate and isokinetic strength of the dominant leg knee flexors and extensors throughout the trial and comparing the results to accredited values from match-play (Gleeson et al., 1998). The strength performance results showed preserved knee flexor strength following the protocol, which has been contradicted in more recent observations during simulated match-play (Rahnama et al., 2003). The average heart rate during the PHISR trial ranged between 168-173 b·min<sup>-1</sup> and was deemed to accurately represent the physiological stress experienced during matches (Gleeson et al., 1998). However, the protocol was not based on actual match-play data to support the durations, speeds or frequency of activity chosen, and was

also deficient in utility movements. Therefore, the PHISR has not been substantially utilised and accepted as a valid soccer-specific fatiguing protocol.

The concept of shuttle running was later applied to a soccer-specific free-running test designed by Nicholas et al. (2000) to more accurately characterise the activity pattern of matches; entitled the Loughborough Intermittent Shuttle Test (LIST). The test was divided into two portions. Part A was a fixed duration comprising five 15 min exercise periods separated by three minutes of recovery. The exercise pattern during each 15 min period (Table 2.4) was based on data recorded from soccer matches (Reilly and Thomas (1976).

**Table 2.4.** Part A activity profile of the LIST (from Nicholas et al., 2000)

| <b>Exercise Mode</b>                             | <b>Speed (km·h<sup>-1</sup>)</b> | <b>Relative Time (%)</b> |
|--|----------------------------------|--------------------------|
| Recovery   | -                                | 4.9                      |
| Walking (walking pace)                           | 5.54                             | 48.1                     |
| Jogging (55% of individual VO <sub>2max</sub> )  | 10.80                            | 24.7                     |
| Cruising (95% of individual VO <sub>2max</sub> ) | 13.79                            | 19.3                     |
| Sprinting (maximal running speed)                | 22.32                            | 3.0                      |

Following Part A, subjects completed Part B which comprised of an open-ended period of intermittent shuttle running over a 20 m distance. Subjects ran at speeds corresponding to 55% and 95% of their predicted VO<sub>2max</sub>, with the speed alternating every 20 m. The subjects maintained the shuttle running until exhaustion (approximately 10 min). To assess the reliability of the test, physiological measurements (heart rate, blood glucose and blood lactate) were recorded during a study in which seven healthy male soccer and rugby players completed the LIST on two separate occasions. The physiological and metabolic responses to the test were similar to those reported during soccer matches (Bangsbo et al., 1991), with

a mean blood lactate value of  $5.7 \text{ mmol}\cdot\text{L}^{-1}$ , mean blood glucose of  $6.3 \text{ mmol}\cdot\text{L}^{-1}$  and mean heart rate of  $170 \text{ b}\cdot\text{min}^{-1}$  ( $70\% \text{ VO}_{2\text{max}}$ ). In terms reproducibility, the study stated 95% agreement for sprint times recorded during Part A and Part B, and no significant differences between the two trials for any of the physiological or metabolic variables measured ( $P > 0.05$ ). The authors also claimed that the LIST accurately simulated the activity profile of soccer, comprising a total distance during Parts A and B of 12.4 km and with 55-60 sprints and turns completed.

However, questions may again be asked about the lengthy periods performing high intensity activity (19.3% cruising and 3% sprinting) which is greater than match-play (~16%) observations (Thatcher and Batterham, 2004). Additionally, the LIST fails to incorporate many of the multidirectional utility movements involved in soccer, such as side-stepping or backwards running. A final limitation to consider is that Part B of the LIST is structured as a run to exhaustion. Consequently, the LIST cannot be standardised to ensure all players complete a full 90 min of exercise and identical total distance, thereby impairing its application for research but perhaps establishing it as a more useful training tool to measure performance. Future development of the protocol could consider replacing Part B of the LIST with an extra Part A to enable the total distance covered and duration of the protocol to be standardised and reflect a 90 min soccer match.

### **2.7.3. Summary**

There have been several attempts to develop treadmill-based and free-running protocols to simulate soccer matches. Treadmill-based protocols will always be hindered by the inability to incorporate utility movements due to the inherent unilateral belt movement of the treadmill. Alternatively, free-running protocols have greater ecological validity with the

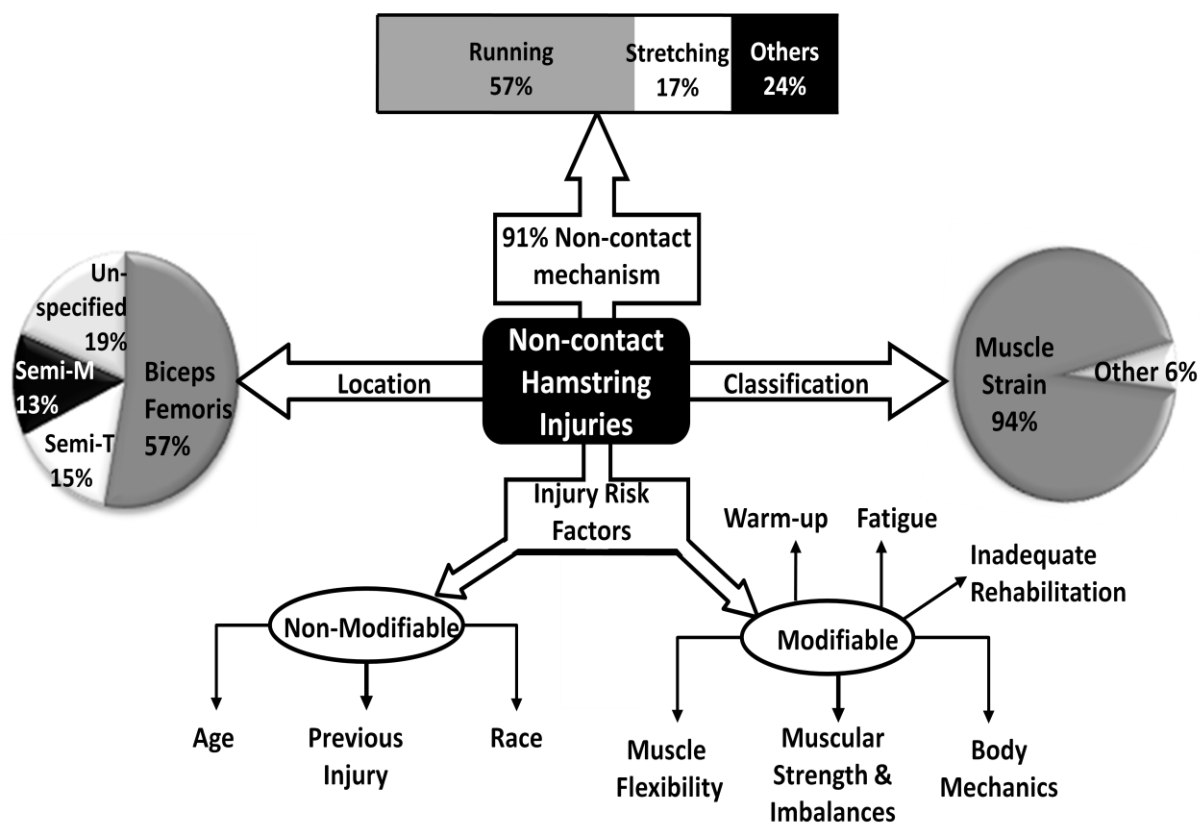
ability to incorporate utility movements. However, they have also failed to simulate soccer match-play due absence of utility movements have not been standardised over a 90 min period reflective of match-play. At present, whether any treadmill-based or free-running protocol can accurately recreate multidirectional soccer match-play fatigue remains highly questionable. Acknowledging the lack of experimental control often associated with free-running protocols, contemporary motion analysis data could be used to devise a new free-running multidirectional soccer-specific fatiguing protocol which may be of benefit for future research.

## **2.8. Overall Summary**

Research has investigated the temporal pattern of injuries in soccer in regard to fatigue, and has created match simulations to further examine factors related to injury potential and mechanisms. Specifically, hamstring strains have shown an increased incidence rate over the past 20 years, and are frequently reported as the most prevalent injury to contemporary, high-level male soccer players, with sprinting identified as the primary mechanism of injury (Woods et al., 2004). They are associated with a high rate of re-injury, causing considerable lost playing time and at subsequent financial costs to clubs. The temporal pattern of hamstring strain incidence during matches has highlighted increased susceptibility to injury during the latter stages of each half (Woods et al., 2004), therefore suggesting fatigue as a potential contributing factor for injury.

Many predisposing factors for hamstring strain injuries have been suggested within the literature, including poor flexibility, muscular strength and imbalances, body mechanics, fatigue, previous injury and age. Although injury may be the result of a single risk factor, it has been suggested to be more likely the result of an interaction between multiple factors

(Hoskins and Pollard, 2005). The aetiological risk factors and epidemiology of hamstring strains in soccer can be summarised in a model (Figure 2.11).



**Figure 2.11.** Model of Non-contact hamstring injuries in soccer. Epidemiology data based on information taken from FA injury audit (Woods et al., 2004). “Semi-T” = semitendinosus, Semi-M = semimembranosus.

Of the various risk factors for hamstring strains, fatigue has been associated to cause detrimental affects to movement and sprinting mechanics (Pinniger et al., 2000), as well as reduced hamstring muscle flexibility and muscular strength (Kraus, 1959). Therefore, fatigue may be a crucial factor related to increased risk of hamstring injury. Research has attempted to investigate the effect of fatigue on the markers of hamstring injury risk, including muscular strength and imbalances (Rahnama et al., 2003; Greig, 2008) and sprinting, as the primary mechanism of injury (Williams and Cavanagh, 1987; Pinniger et al., 2000). However, the studies have failed to use fatiguing protocols representative of the

multidirectional nature of soccer match-play whilst also replicating both the physiological responses and activity profile. This may impair the ability to extrapolate findings to soccer, and consequently impede progress in developing appropriate injury prevention programmes.

The experiments presented in this thesis aimed to initially develop a new free-running soccer simulation that can replicate the movement demands and physiological responses of contemporary soccer match-play. The simulation has then been used to investigate the effect of soccer-specific fatigue on the primary aetiological risk factors (muscular strength and imbalances) and mechanism (sprinting) of hamstring strain injury. The information obtained was then used to create and evaluate an innovative strategy for hamstring injury prevention, aiming to reduce the risk of hamstring strains in soccer.

## **Chapter 3. Development of a New Soccer-specific Match Simulation.**

### **3.1. Introduction**

Soccer is characterised by an intermittent and irregular nature and pattern of play. Modern day sports scientists have attempted to replicate the demands of soccer match-play using simulations (Drust et al., 2000a; Nicholas et al., 2000; Thatcher and Batterham, 2004; Greig et al., 2006), based on motion analysis of games where exercise is classified according to type, intensity, duration and frequency (Reilly, 1994). Players' physiological responses to the simulations have been assessed to provide information regarding individuals' respective strengths and weaknesses. This information has then been used as the basis to develop optimal training and injury prevention strategies (Svensson and Drust, 2005).

Research investigating the demands of soccer has adopted either treadmill-based (Drust et al., 2000a; Thatcher and Batterham, 2004; Greig et al., 2006) or free-running (Nicholas et al., 2000) protocols. Treadmill-based soccer simulations have either replicated the physiological responses (eg. heart rate: 168 b·min<sup>-1</sup>, Drust et al., 2000a; 166 b·min<sup>-1</sup>, Thatcher and Batterham, 2004) but not the activity profile of soccer (92 and 360 changes in intensity over 90 min; Drust et al., 2000a; Thatcher and Batterham, 2004), or have replicated the activity profile (1170 changes in intensity over 90 min; Greig et al., 2006) but not the physiological response (~130 b·min<sup>-1</sup>; Greig et al., 2006). Additionally, recent activity profiles (Drust et al., 2000; Greig et al., 2006) have been based on match-play motion analysis recorded prior to 1991. Consequently, data were captured using the traditional method of video cameras, therefore increasing the likelihood of incomplete recordings and activity profiles which causes extrapolation of work rates based on few players and for limited periods during a match. Furthermore, data obtained prior to 1991 may not reflect the modern game. For example, Strudwick and Reilly (2001) reported that



contemporary players cover ~1.5 km further distance per match compared with average match-play distance covered prior to 1992.

Regarding free-running soccer simulations, the Loughborough Intermittent Shuttle Test (LIST) (Nicholas et al., 2000) is perhaps the most commonly utilised. The LIST has been shown to elicit both physiological response ( $170 \text{ b}\cdot\text{min}^{-1}$ ) and movements demands (incorporating turns) inherent in soccer (Nicholas et al., 2000). However, the protocol includes a run to exhaustion during the final ~10 min period, therefore distance covered and total activity time cannot be standardised to reflect a 90 min match. Additionally, only ~150 deceleration movements are performed during the structured 75 min portion of the LIST which is substantially lower than the 496 recently observed by Bloomfield et al. (2008) during matches.

Considering the limitations of previous soccer simulations, the aim of this study was to develop a new standardised soccer-specific match simulation based on contemporary soccer and able to recreate match-play demands. The simulation was assessed by comparing the activity profile and physiological responses with that of accredited match observations from peer reviewed literature. The development of the simulation may have practical implications for use in training and as a research tool to investigate injury risk and prevention.

### **3.2. Pilot Work**

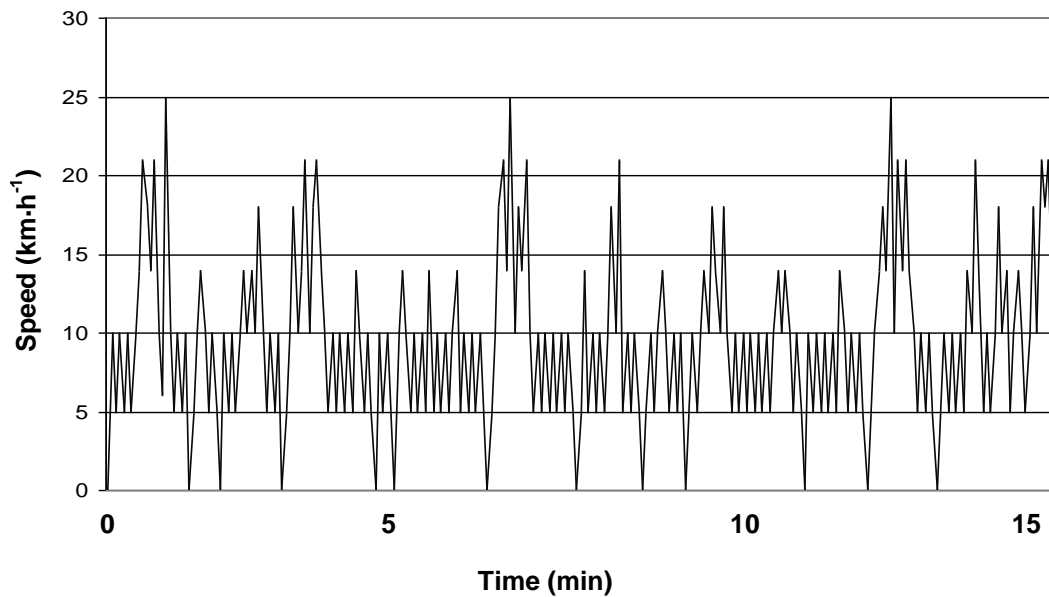
The first stage in developing a new soccer-specific match simulation involved obtaining and analysing modern match-play data. English Championship level matches during the 2007/2008 soccer season were monitored for one professional team using a computerised, semi-automatic video match analysis image recognition system (data supplied by Prozone

®, Leeds, England and published with formal permission of the company). This method involved recording positional data of every player every 1/10<sup>th</sup> of a second during matches using cameras positioned around the playing field. The captured data were systematically analysed using propriety software to provide comprehensive data on each individual, including distance covered and average speed. Impellizzeri et al. (2006) reported the accuracy and validity of this recognition system for the quantification of match-related physical activities in soccer for research and practical purposes.

A 15 min activity profile was developed from the match-play data, which was repeated six times during a simulated 90 min game. The distance, speed, and frequency of each exercise intensity were calculated from the data which was input into a programmable motorised treadmill (LOKO S55, Woodway, GmbH; Steinackerstraße, Germany). This equipment was selected as has previously been shown to have good reliability in simulating the activity profile of soccer match-play (Greig et al., 2006). Table 3.1 shows the average duration of each activity performed during the 15 min activity profile and data from actual match-play, with Figure 3.2 representing the 15 min activity profile.

**Table 3.1.** Data from 15min activity profile of treadmill protocol compared with equivalent match-play data. HS = High-speed run

| Activity                       | Total Time (s)     |                 | Total Distance (m) |                 | Frequency          |                 |
|--------------------------------|--------------------|-----------------|--------------------|-----------------|--------------------|-----------------|
|                                | Treadmill Protocol | Match-play data | Treadmill Protocol | Match-play data | Treadmill Protocol | Match-play data |
| Stand (0km·h <sup>-1</sup> )   | 39                 | 41.4            | -                  | -               | 13                 | 13              |
| Walk (6km·h <sup>-1</sup> )    | 468                | 524.1           | 0.63               | 0.60            | 78                 | 94              |
| Jog (12km·h <sup>-1</sup> )    | 291                | 282.6           | 0.92               | 0.97            | 97                 | 110             |
| Run (15km/h)                   | 56                 | 48.7            | 0.15               | 0.24            | 28                 | 42              |
| Stride (18km·h <sup>-1</sup> ) | 28                 | 30.8            | 0.11               |                 | 14                 |                 |
| HS (21km·h <sup>-1</sup> )     | 26                 | 24.3            | 0.22               | 0.45            | 13                 | 13              |
| Sprint (25km·h <sup>-1</sup> ) | 6                  | 4.4             | 0.19               |                 | 3                  | 3               |
| <b>Total Time</b>              | <b>912</b>         | <b>956.3</b>    | <b>2.22</b>        | <b>2.26</b>     | <b>245</b>         | <b>275</b>      |



**Figure 3.1.** Schematic representation of the 15 min soccer-specific activity profile

In the second stage of development, four semi-professional soccer players, free from injury at the time of testing, completed the newly developed soccer-specific treadmill protocol. To investigate the fatiguing effect of the protocol, heart rate, sprint performance and isokinetic dynamometry of the knee flexors and extensors were recorded during the 90 min.

Heart rate has been shown to provide a useful index of overall physiological strain related to soccer match-play (Stølen, 2005). This was continuously monitored using short-range radio telemetry (Polar Team System, Polar Electro; Kempele, Finland), with mean heart rate later calculated for each 45 min half. As a comparable measure of performance related to match observations (Stølen et al., 2005; Bangsbo et al., 2006), subjects performed three 10 m sprints on a non-slip indoor surface at 15 min intervals throughout the exercise protocol. Finally, lower limb muscular strength was assessed using isokinetic dynamometry (Biodex System 3, Biodex Medical, Shirley, NY) to provide an indication of local muscular fatigue and to compare with previous research using alternative match simulations (Rahnama et al., 2003; Greig, 2008). Isokinetic peak torque (PT) of subjects dominant leg;

their ‘kicking’ leg, was performed for concentric knee flexion (conH) and extension (conQ), and eccentric knee flexion (eccH). This routine was performed pre-exercise, at half-time and post-exercise. Further details of the isokinetic dynamometry testing methodology employed will be described in Chapter 4.

### 3.3. Pilot Test Results

Results showed an average heart rate of  $119 \pm 9$  b·min<sup>-1</sup> throughout the 90 min protocol. Furthermore, there were no apparent effects of fatigue demonstrated in relation to sprint performance (Table 3.2) or muscular strength of the knee flexors and extensors (Table 3.3).

**Table 3.2.** Sprint times during the new 90 min soccer-specific treadmill protocol

| <b>Time (min)</b> | <b>Sprint Time (s) Mean ± SD</b> |
|-------------------|----------------------------------|
| 0                 | 1.682 ± 0.018                    |
| 15                | 1.723 ± 0.014                    |
| 30                | 1.647 ± 0.025                    |
| 45                | 1.632 ± 0.038                    |
| 46                | 1.681 ± 0.033                    |
| 60                | 1.635 ± 0.019                    |
| 75                | 1.598 ± 0.011                    |
| 90                | 1.568 ± 0.009                    |

**Table 3.3.** Isokinetic strength profiling for the knee flexors and extensors

| <b>Time (min)</b> | <b>conQ PT (N·m)</b> | <b>conH PT (N·m)</b> | <b>eccH PT (N·m)</b> |
|-------------------|----------------------|----------------------|----------------------|
|                   | <b>Mean ± SD</b>     | <b>Mean ± SD</b>     | <b>Mean ± SD</b>     |
| <b>0</b>          | 248.9 ± 47.5         | 194.0 ± 33.9         | 243.4 ± 42.5         |
| <b>45</b>         | 238.6 ± 41.7         | 178.0 ± 43.9         | 239.0 ± 44.2         |
| <b>90</b>         | 252.9 ± 48.9         | 188.4 ± 41.0         | 246.2 ± 35.5         |

Edwards and Clark (2006) reported a mean heart rate of  $162 \text{ b}\cdot\text{min}^{-1}$  for English semi-professional soccer players during matches. The average response recorded during pilot testing using the new intermittent treadmill protocol based on contemporary soccer match-play work rates was  $119 \text{ b}\cdot\text{min}^{-1}$ . Furthermore, research has reported impaired sprinting performance (Mohr et al., 2003; 2004), and reduced eccentric hamstring (Rahnama et al., 2003; Greig, 2008) and concentric quadriceps and hamstring strength (Rahnama et al., 2003) over time during soccer simulations in contrast to current results.

The new soccer-specific treadmill protocol failed to replicate basic physiological and local muscular fatigue effects of match-play despite being based on contemporary work rates of high-level soccer. This may be due to a number of factors. Firstly, by using a motorised treadmill this may have reduced the fatiguing effect by automatically administering acceleration and deceleration demands. During matches, research has observed 496 deceleration movements (Bloomfield et al., 2008) which have been postulated to increase the eccentric stress. This may also be an important factor associated with injury risk (Woods et al., 2004). The protocol could alternatively be performed on a non-motorised treadmill which has the benefits of significantly faster self-performed acceleration and deceleration (Drust et al., 2000b). However, this equipment inhibits the ability to standardise distance covered and time spent performing each movement intensity. Therefore, as a fixed exercise model is fundamental for work in this thesis, this suggestion would not be appropriate.

A second important limitation to employing a treadmill-based protocol is that the equipment generates a linear manner of activity, therefore inhibiting utility movements as are inherent to soccer match-play. Up to 36.9% of total distance covered during soccer is

performed using utility movements (Thatcher and Batterham, 2004). This has been reported to significantly increase the physiological load, metabolic cost and muscular fatigue in soccer (Bangsbo, 1994a; Kirkendall, 2000). Therefore, given the results of the pilot testing, the inclusion of utility movements may be crucial for increasing the demands of match-play, whilst also better replicating the multidirectional nature of soccer.

After reviewing the results and conclusions of the pilot testing, it was decided to use the initial match-play data as the basis to develop a free-running 90 min version of a recently developed soccer-specific aerobic field test (SAFT<sup>90</sup>).

### **3.4. Methods**

#### Participants

Eight male semi-professional soccer players (Mean  $\pm$  SD; Age:  $22 \pm 4$  yrs; Height  $184.8 \pm 4.8$ cm; Body Mass  $78.3 \pm 5.4$ kg;  $VO_{2max}$ :  $57.6 \pm 5.1$  ml·kg<sup>-1</sup>·min<sup>-1</sup>) were recruited to take part in the investigation. All players regularly completed on average two squad training sessions and two matches per week. Subjects were included in the study if they were not injured or rehabilitating from an injury at the time of testing. Ethical approval for the study was obtained in accordance with the Departmental and University ethical procedures, and written, informed consent was given by the subjects prior to data collection.

#### Experimental Design

Subjects completed a 90 min version of a recently developed free-running soccer-specific aerobic field test (SAFT<sup>90</sup>). The SAFT<sup>90</sup> was divided into two 45 min periods interceded by a 15 min passive rest period (half-time). During the SAFT<sup>90</sup>, subjects were tested and

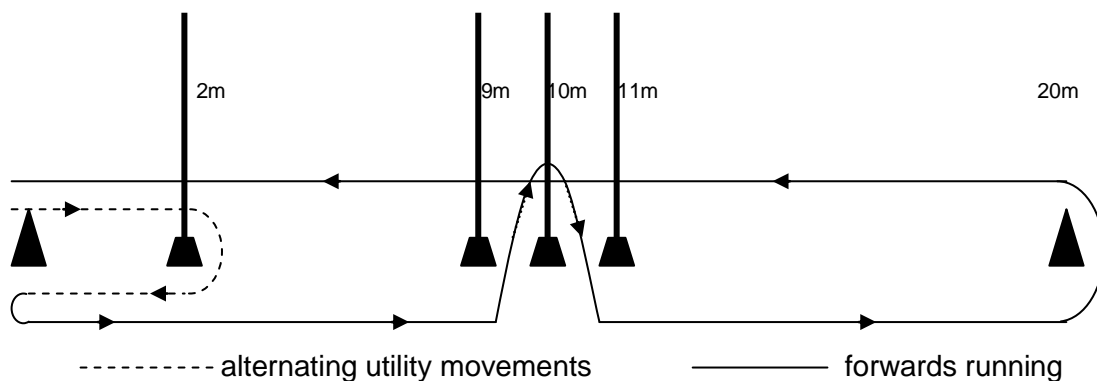
monitored for various measures of physiological response commonly associated with soccer match-play.

The subjects performed no vigorous exercise 24h prior to testing, nor consumed any caffeine or alcohol. Testing was conducted at the beginning of the 2007/2008 English soccer season. The training load and amount of match-play performed was as standard to the competitive season, comprising on average two training sessions and matches a week.

All testing was performed in a temperature controlled biomechanics laboratory. Prior to testing, all subjects had previously attended the laboratory for a 30 min familiarisation with the SAFT<sup>90</sup> exercise protocol. During this time, subjects were also familiarised with the testing methodologies employed in the study to record their physiological responses.

### Exercise Protocol

The SAFT<sup>90</sup> was developed to replicate the physiological, local muscular demands and multidirectional nature of soccer. The simulation was based on contemporary time-motion analysis data of 2007 English Championship Level matches (Prozone<sup>®</sup>). The test incorporates utility movements and frequent acceleration/deceleration over a 20 m shuttle run with the incorporation of four positioned poles that subjects navigate (Figure 3.2).



**Figure 3.2.** A diagrammatic representation of the SAFT<sup>90</sup> field course



The course is performed with the subject performing either backwards running or sidestepping around the first field pole, followed by forward running through the course, navigating the middle three field poles using a cutting action. A 15 min activity profile was developed using the English Championship Level match-play data which was repeated a total of six times over the 90 min. The activity profile was performed in a randomised and intermittent fashion, controlled using verbal signals via an audio CD, and incorporates 1269 changes in speed (every 4.3 s), and 1350 changes in direction over the 90min. The frequency in changes of activity during the SAFT<sup>90</sup> is in concurrence with 1250 activities observed during match-play (Mohr et al. 2003).

Table 3.4 shows the distances covered at each of the movement activity during the SAFT<sup>90</sup> and the corresponding match-play data with which the protocol was based on.

**Table 3.4.** Distances covered and time spent performed each activity during SAFT<sup>90</sup> and equivalent Match-play Data

| Activity                                   | Distance (km)      |              | Distance (%)       |              | Time (s)           |                | Time (%)           |            |
|--|--------------------|--------------|--------------------|--------------|--------------------|----------------|--------------------|------------|
|  | SAFT <sup>90</sup> | Match-play   | SAFT <sup>90</sup> | Match-play   | SAFT <sup>90</sup> | Match-play     | SAFT <sup>90</sup> | Match-play |
| <b>Standing (0.0 km·h<sup>-1</sup>)</b>    | 0.00               | 0.02         | -                  | -            | 240                | 248.14         | 4.28               | 4.36       |
| <b>Walking (5.0 km·h<sup>-1</sup>)</b>     | 3.36               | 3.60         | 31.82              | 31.83        | 2958.80            | 3150.82        | 52.77              | 55.42      |
| <b>Jogging (10.3 km·h<sup>-1</sup>)</b>    | 5.58               | 5.81         | 52.84              | 50.86        | 2002.44            | 1915.82        | 35.74              | 33.69      |
| <b>Striding (15.0 km·h<sup>-1</sup>)</b>   | 1.50               | 1.46         | 14.02              | 15.30        | 360.00             | 344.36         | 6.42               | 6.06       |
| <b>Sprinting (≥20.4 km·h<sup>-1</sup>)</b> | 0.34               | 0.27         | 1.14               | 1.70         | 44.16              | 26.55          | 0.79               | 0.47       |
| <b>Total:</b>                              | <b>10.78</b>       | <b>11.08</b> | <b>99.82</b>       | <b>99.69</b> | <b>5605.40</b>     | <b>5685.69</b> | <b>100</b>         | <b>100</b> |

### Maximal Oxygen Uptake Test and Expired Gas Analysis

Prior to performing the SAFT<sup>90</sup>, subjects performed a maximal oxygen uptake ( $VO_{2max}$ ) test to establish their  $VO_{2max}$ . The test was performed on a motorised treadmill (Woodway ELG55, Weil an rheim, Germany). Prior to commencing the test, the gas analyser (Cortex Metamax 3B, Leipzig, Germany) was calibrated in accordance with the user manual, and the subjects completed a short warm-up on the treadmill, consisting of light jogging. The incremental test began at  $10 \text{ km}\cdot\text{h}^{-1}$ , increasing by  $1 \text{ km}\cdot\text{h}^{-1}$  every minute until volitional exhaustion. Breath-by-breath data was smoothed over 15 s intervals and the peak value was recorded as a  $VO_{2max}$  following procedures by Chinatal et al. (2008).

Expired air was collected and analysed during the first 15 min of each half of the SAFT<sup>90</sup> to determine oxygen consumption (Cortex Metamax 3B, Leipzig, Germany). Prior to exercise the system was calibrated according to the manufacturer's specifications. The gas analysers were calibrated using ambient air (assumed to be 20.93%  $O_2$  and 0.03%  $CO_2$ ) and alpha standard gases (16.00%  $O_2$  and 4.96%  $CO_2$ ; BOC, Guildford, UK) and a bi-directional digital turbine (accuracy of 2%), used to measure flow rate, was calibrated with a 3-litre syringe (Cosmed Srl, Italy). The gas analyser has  $O_2$  and  $CO_2$  sensors that have a response time of <120 ms and an accuracy of 0.01 and 0.03%, respectively. One 15 min activity period at the start of each half of the SAFT<sup>90</sup> were chosen to collect expired air, due the discomfort to the subjects navigating the field course wearing the equipment.

### Heart Rate

Heart rate was continuously monitored throughout the SAFT<sup>90</sup> using short-range radio telemetry (Polar Team System, Polar Electro; Finland), sampled every 5 s. Mean heart rate was later calculated for each 45 min half, removing data during the half-time interval.

### Core Temperature

Core body temperature was measured in the intestine using a silicon coated pill (CorTemp, HQ Inc, Florida, USA). The pill consisted of a temperature sensitive quartz crystal oscillator with a silver oxide battery, covered with silicone rubber, which transmitted a continuous, low-frequency radio wave which varied with temperature. The wave was detected by an external receiver and data logger placed on the lumbar spine. The pills were calibrated by the manufacturer with an accuracy of  $\pm 0.1$  °C, and a linear correlation that exceeds 0.999 between signal frequency and temperature (O'Brien et al., 1998). The ingestible pill was swallowed by the subjects four hours prior to beginning the SAFT<sup>90</sup> following manufacturer guidelines. This was to ensure it would have progressed past the stomach and be insensible to hot or cold liquids subsequently swallowed. Subjects were allowed a meal when ingesting the pill, but only consumed water thereafter. Throughout the experimental trial, core body temperature was measured at 5 min intervals.

### Fluid Loss and Intake

To determine sweat loss during the simulation, players' dry nude body weight was recorded before and immediately after exercise using non-digital weighting scales (SECA Balance scales, SEC01, Vogel & Halke, Hamburg Germany). The players were allowed to drink water ad libitum during the half- time interval, and their water intake recorded.

### Blood Lactate Measurement and Analysis

Blood lactate concentration was measured at rest, following warm-up, at 15 min intervals throughout the SAFT<sup>90</sup> and at 5 min intervals during the half-time period including immediately prior to beginning the second half. Before collecting a sample, the site was

cleaned using an alcohol wipe, the skin punctured with a lancet and the blood samples collected into a capillary tube. Samples were immediately analysed for whole blood lactate concentration using an automatic blood lactate analyser (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, Ohio), calibrated prior to analysing samples according to the manufacturer's guidelines. Following collection of the blood samples, alcohol and sterile pads were used to clean and dry the site.

### Sprint Performance

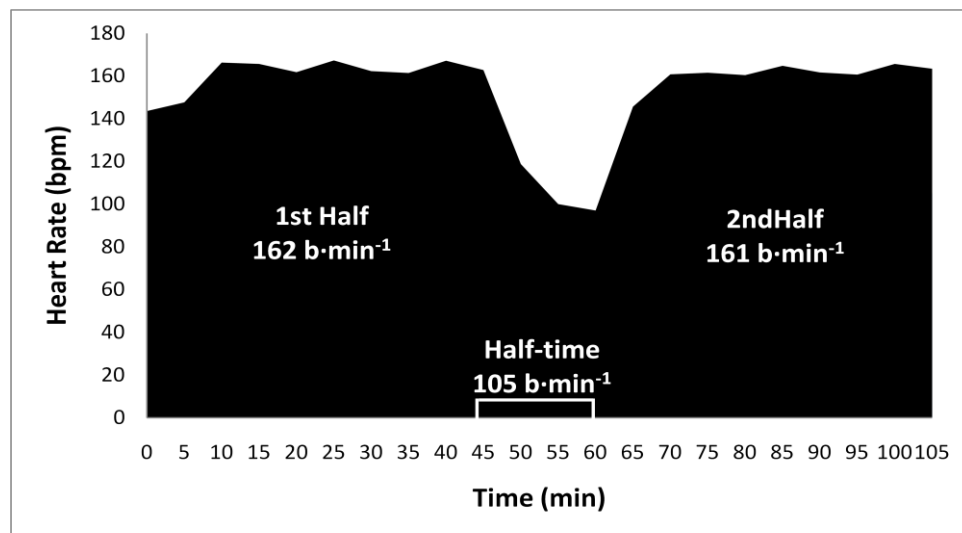
During the sprint phases of the SAFT<sup>90</sup> (ie. two every 15 min activity period), 10 m straight-line sprint times were recorded from a 3 m rolling start and later averaged for each 15 min period. Times were recorded using infrared photo-electric cells which were positioned as gates across the SAFT<sup>90</sup> course, interfaced to a timing system (Newtest System, Newtest Oy, Oulu, Finland).

### Data Analysis

Descriptive statistics of outcome measures included means and standard deviations ( $\pm$ SD). Before using parametric tests, the assumption of normality was verified using the Kolmogorov–Smirnov test. One way analysis of variance (ANOVA) for repeated measures were used to examine changes in sprint performance and physiological responses over time. Post hoc comparisons to identify significant differences between means were made using paired samples t-tests. Statistical analysis was processed using SPSS statistical software (version 14.0 Chicago, IL) with significance levels set at  $P \leq 0.05$ .

### 3.5. Results

Heart rate (HR) during the SAFT<sup>90</sup> protocol (Figure 3.3) averaged  $162 \pm 2 \text{ b}\cdot\text{min}^{-1}$  ( $82.9 \pm 1.5 \%$  of maximum HR) and oxygen consumption  $38.9 \pm 4.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  ( $69.1 \pm 11.1 \%$   $\text{VO}_{2\text{max}}$ ). Average HR during the first 5 min of each half was significantly lower ( $P < 0.01$ ) than any other measurements during the 90 min simulation. The average HR during the 1<sup>st</sup> half was  $162 \pm 6 \text{ b}\cdot\text{min}^{-1}$  and  $161 \pm 6 \text{ b}\cdot\text{min}^{-1}$  during the 2<sup>nd</sup> half, which equated to 83.3 % and 82.4 % of maximum HR during the 1<sup>st</sup> and 2<sup>nd</sup> half, respectively.



**Figure 3.3.** Example of single subjects' heart rate response during the SAFT<sup>90</sup>

Blood lactate concentration significantly increased from  $1.39 \text{ mmol}\cdot\text{L}^{-1}$  at rest to an average  $4.7 \pm 1.4$  and  $4.0 \pm 1. \text{ mmol}\cdot\text{L}^{-1}$  during the 1<sup>st</sup> and 2<sup>nd</sup> halves, respectively ( $P < 0.05$ ). The average blood lactate concentration during the 1<sup>st</sup> half was also significantly higher than the 2<sup>nd</sup> half ( $P < 0.05$ ).

Core body temperature significantly increased over time during the simulation, from  $37.2 \pm 0.3 \text{ }^\circ\text{C}$  at rest to  $38.9 \pm 0.3$  and  $38.3 \pm 0.4 \text{ }^\circ\text{C}$  at the ends of the 1<sup>st</sup> and 2<sup>nd</sup> halves, respectively ( $P < 0.01$ ). However, there was no significant difference between core body temperature at the ends of each half ( $P > 0.05$ ).

There was a significant reduction in body weight during the SAFT<sup>90</sup> after correcting for average fluid intake (0min: 78.3 ± 5.4 ml vs 105min: 76.8 ± 5.7;  $P < 0.01$ ; Table 3.5).

**Table 3.5.** Weight and fluid loss during SAFT<sup>90</sup>

|   |            |
|---|------------|
| Weight pre-SAFT <sup>90</sup> (kg):                             | 78.3 ± 5.4 |
| Weight post-SAFT <sup>90</sup> (kg):                            | 77.2 ± 5.6 |
| Weight post-SAFT <sup>90</sup> corrected for fluid intake (kg): | 76.8 ± 5.7 |
| Total fluid loss (l):   | 1.5 ± 0.4  |
| Fluid Loss % of body weight:                                    | 2.0 ± 0.7  |

Sprint performance decreased over time during the SAFT<sup>90</sup> ( $P < 0.01$ ). There was a significant decrease in maximal sprint performance by 4.1 ± 2.1 % at the end of the 1<sup>st</sup> half of the SAFT<sup>90</sup> (0min: 1.67 ± 0.08 vs 45min: 1.77 ± 0.12 s;  $P < 0.01$ ), and a further 3.0 ± 2.1 % decrease by the end of the 2<sup>nd</sup> half (60min: 1.76 ± 0.12 vs 105min: 1.82 ± 0.13 s;  $P < 0.05$ ). Overall, there was a 7.1 ± 2.6 % decrease in sprint performance during the 90 min match simulation ( $P < 0.01$ ).

### 3.6. Discussion

The aim of this investigation was to devise a new standardised soccer-specific match simulation based on the demands of modern soccer which would then be used to investigate injury risk and prevention. Following pilot research, a new 90 min soccer-specific free-running match simulation (SAFT<sup>90</sup>) was developed.

The activity duration of the soccer simulation was 90.43 min. The total distance covered during the 90 min was 10.78 km, performed using a variety of frequently changing movement intensities observed during match-play (standing, walking, jogging, striding and

sprinting). The distances, speed, and time spent performing each movement intensity was based closely on time motion analysis data obtained from 2007 English Championship Level matches (Prozone<sup>®</sup>). The proportion of distance covered at the various movement intensities is similar to that observed in contemporary high-level English soccer matches (Thatcher and Batterham, 2004).

The magnitude of the physiological response to the SAFT<sup>90</sup> (fluid loss, heart rate, blood lactate concentration, and core body temperature) increased as a function of exercise duration suggesting a cumulative effect of physiological strain. To evaluate the SAFT<sup>90</sup>, the physiological responses to the simulation were compared to published data obtained from actual match-play. Regarding the basic physiological response of heart rate, a mean value of 162 b·min<sup>-1</sup> (82.9% HR<sub>max</sub>) was observed during the SAFT<sup>90</sup>. This is consistent with previous soccer match-play observations using high-level male players (Table 3.6).

**Table 3.6.** Heart rate response during soccer match-play

| Study                 | Level/Country       | Type of Match | HR (b·min <sup>-1</sup> ) |
|-----------------------|---------------------|---------------|---------------------------|
| Edwards & Clark, 2006 | Semi-pro/uni (Eng)  | Friendly      | 156                       |
| Bachev et al., 2005   | Junior InterN (Bul) | Friendly      | 156                       |
| Mohr et al., 2004     | Div 4 (Den)         | Friendly      | 160                       |
| Ali & Farrally, 1999  | Semi-pro (Scot)     | League        | 172                       |
| Ogushi et al., 1993   | Semi-pro (Jap)      | Friendly      | 162                       |
| Bangsbo et al., 1991a | Div 1/2 (Den)       | League        | 159                       |
| Van Gool et al.,1988  | Uni (Bel)           | Friendly      | 167                       |
| Reilly, 1986          | League (Eng)        | Friendly      | 157                       |



Oxygen consumption measured during the two 15 min periods at the start of the first and second halves of the SAFT<sup>90</sup> was 38.9 ml·kg<sup>-1</sup>·min<sup>-1</sup>, corresponding to 69.1% of VO<sub>2max</sub>. This result is comparable with mean values of 70% VO<sub>2max</sub> attributed to soccer match-play (Mohr et al., 2004). However, it should be considered that research is yet to provide firm evidence of an accurate measure of oxygen uptake during matches due to short sampling periods and performance-inhibiting the gas collection device (Kawakami et al., 1992).

Average blood lactate concentration was 4.7 mmol·L<sup>-1</sup> for the first half of the free-running soccer simulation which decreased during the second half to 4.0 mmol·L<sup>-1</sup>. Previous measurements recorded during match-play have reported average blood lactate concentrations of 3-6 mmol·L<sup>-1</sup> (Krustrup et al., 2003 and 2006), and specifically with values of 3.7 mmol·L<sup>-1</sup> at the end of high-level English soccer matches (Edwards and Clark, 2006). The disparity in values reported within the literature to that observed during the SAFT<sup>90</sup> may be attributed to differing intensity of activity performed immediately prior to sampling (Bangsbo et al., 1991).

During the SAFT<sup>90</sup>, core body temperature recorded at the ends of the first and second half were 38.9 and 38.8 °C, respectively. These values correspond with measurements taken at the ends of each half of actual matches (38.7 and 38.7 °C; Mohr et al., 2004). Related to core body temperature, players lost 1.5 kg during the 90 min simulation which corresponded to a 2.0% decrease of their body weight through fluid loss. This is comparable with research observations during competitive matches where players experienced a 1.8 kg (2.2%) decrease in body weight (Mohr et al., 2004) and a 1.9% decrease in body weight through fluid loss during English high-level competitive matches (Edwards and Clark, 2006). Hypohydration amounting to ~2% of body mass during soccer

has been shown to result in significantly reduced sprinting performance (Magal et al., 2003; Mohr et al., 2004), which was also observed during the SAFT<sup>90</sup>. However, it should be considered that environmental conditions differ between field and laboratory settings which may affect core body temperature and consequently fluid loss results.

In relation to sprinting performance, results showed decreased performance as a function of time during the SAFT<sup>90</sup> to be 95.9 and 92.3% of maximal sprinting speed at the ends of the first and second halves, respectively. This concurs with previous research by Krustup et al. (2003) investigating sprint performance during actual match-play who reported a ~4% reduction in 30 m sprint times at the end the second half. Furthermore, a 9% decrease in sprinting performance has been observed between the first and last 15 min period of competitive games over a ~13 m distance (Bangsbo and Mohr, 2005). The decrement in sprint performance observed during the SAFT<sup>90</sup> may be related to epidemiological research observations concerning hamstring injury risk. Woods et al. (2004) reported that almost half of all hamstring strains occur during the final stages of the first and second halves of soccer matches, with sprinting identified as the primary mechanism of injury. However, further investigation is required to better understand potential alterations in either technique or muscular strength as may be related to increased hamstring injury risk.

The close similarities between physiological responses and impaired performance observed during the present investigation with corresponding values reported from actual match-play support the accuracy of the SAFT<sup>90</sup> at replicating the demands of soccer. To further evaluate the SAFT<sup>90</sup> as a match simulation and justify its use in future research it was also compared to alternate soccer simulations. Drust et al. (2000a) developed a 90 min intermittent treadmill protocol based on work-rates of professional soccer players recorded by Reilly and Thomas (1976). The physiological responses to the protocol were shown to

reflect corresponding match-play values. However, the activity profile incorporated only 92 changes in movement intensity over the 90 min, compared to 1269 performed during the SAFT<sup>90</sup> and over 1250 activities observed during match-play (Mohr et al. 2003). The consequence of the reduced frequency of activity performed using the treadmill protocol created substantially longer time spent performing individual movement bouts (walking 35.3 s, jogging 50.3 s, cruising 51.4 s and sprinting 10.5 s). Therefore, substantially greater amount of time was spent performing the high intensity activities, totalling over 50% of the total distance covered compared with ~16% observed during actual matches (Thatcher and Batterham, 2004) and just over 15% during the SAFT<sup>90</sup>. Also, the players completed a total distance in excess of 18 km during the 90 min treadmill protocol which is substantially further than covered during match-play (10-12 km; Stølen et al., 2005). The increased high intensity activity and total distance of the protocol by Drust et al. (2000a) may have created additional physiological fatigue to match the extra demands imposed by the multidirectional and more frequently intermittent nature of actual match-play and the SAFT<sup>90</sup>.

In a more recent, yet similar protocol, Thatcher and Batterham (2004) validated an intermittent sport-specific exercise protocol (SSEP) for elite youth soccer players. The SSEP was based on motion analysis obtained from the same subject population using camcorders to record match-play. The protocol was developed to be performed on a non-motorised treadmill, which has the advantage of significantly faster acceleration and deceleration periods, allowing individuals to reach their maximal sprinting speed (Drust et al., 2000a). The activity profile utilised five movement intensities (standing; walking; jogging; running; sprinting) which were arranged into two bouts of 9x5 min repeating cycles separated by a 15 min rest period (half-time).

To validate the protocol, six male soccer players completed two trials; on one occasion performing the SSEP and on the second completing in a soccer match. During both trials, heart rate data were recorded, and blood lactate concentration and expired air were measured during the SSEP trial. The results showed comparable mean heart rate response between SSEP protocol and actual match-play (match-play:  $166 \pm 9$  vs SSEP:  $166 \pm 12$   $\text{b}\cdot\text{min}^{-1}$ ;  $P > 0.05$ ). The mean response for  $\text{VO}_{2\text{max}}$  during the SSEP was  $70 \pm 3$  %, and blood lactate concentrations were measured at  $5.37 \pm 1.15$  and  $4.74 \pm 1.25$   $\text{mmol}\cdot\text{L}^{-1}$  recorded during the first and second halves of the protocol, respectively. The findings supported the validity of the SSEP to replicate the physiological responses of soccer.

However, it should be considered that only physiological responses (heart rate, expired air and blood lactate) were measured during the trials. There were no measurements recorded to determine local muscular fatigue or performance during the protocol, such as sprinting, to compare against match-play observations in the literature. Furthermore, the activity profile developed by Thatcher and Batterham (2004) included only ~360 discrete bouts of activity during the 90 min, compared with over 1250 previously reported (Mohr et al., 2003), and covered 22% of total distance at high intensity as opposed to ~16% during matches (Thatcher and Batterham, 2004).

Given the low frequency activity profile used in the protocols by Drust et al. (2000a) and Thatcher and Batterham (2004), Greig et al. (2006) devised an alternate football-specific treadmill-based intermittent protocol based on match-play notational analysis by Bangsbo et al. (1991) which encompassed 1170 changes in movement intensity over 90 min. It was hypothesised by Greig et al. (2006) that the protocol would more accurately reflect the

activity profile and mechanical fatigue associated with soccer due to more frequent acceleration/deceleration movements.

To validate the protocol, physiological responses (heart rate and blood lactate) were measured using 10 semi-professional soccer players. Results revealed that mean heart rate only increased from 125  $\text{b}\cdot\text{min}^{-1}$  during the first 15 min of the intermittent protocol to 135  $\text{b}\cdot\text{min}^{-1}$  during the final 15 min. Also, blood lactate concentrations peaked at just 1.4  $\text{mmol}\cdot\text{L}^{-1}$  at the end of the 90 min. These results are clearly substantially below values recorded during actual soccer match-play, and those from the present investigation. This finding was attributed by the authors to situational factors and the lower emotional stress experienced by completing the activity profile in the laboratory as opposed to during competitive matches (Whitehead et al., 1996). Alternatively, the lower physiological responses may be attributed to the absence of utility movements and self-performed acceleration/deceleration due to the use of a motorised treadmill.

The validation study by Greig et al. (2006) also attempted to assess the local muscular fatigue experienced to the intermittent treadmill protocol by recording electromyography of the biceps femoris. Results showed a significant increase in the biceps femoris activity, producing greater muscular output to achieve the same standardised workload. Greig et al. (2006) proposed that the increased muscular activity of the biceps femoris may create inhibition of the quadriceps muscle group to alter kinematics of movement and thus increase injury risk. This fatigue effect observed was furthermore linked to observations of increased susceptibility to hamstring strain injury during the latter stages of soccer matches (Woods et al., 2004). Greig et al. (2006) concluded that the intermittent treadmill protocol

accurately replicated the activity pattern and mechanical response of match-play, despite the lowered physiological responses, and may have implications for hamstring injury risk.

Aside from treadmill-based soccer simulations, research has also attempted to characterise the activity profile and demands of match-play using a 90 min free-running test (the LIST) developed by Nicholas et al. (2000). The test was divided into two portions. Part A was a fixed duration consisting five, 15 min exercise periods separated by three minutes of recovery, with the activity profiles based on data by Reilly and Thomas (1976). Subjects then performed Part B of the protocol, an open ended period of intermittent shuttle runs over 20 m at speeds corresponding to 55% and 95% of their predicted  $VO_{2max}$ . The speed was altered every 20 m, with subjects continuously repeating this pattern until exhaustion, within approximately 10 min.

The LIST has been validated with the physiological responses stated by the authors to accurately reflect those recorded in the literature during matches (Nicholas et al., 2000). However, just over 22% of total distance covered during the LIST was performed at the higher intensities of cruising (19.3%) and sprinting (3%), greater than the ~16% high intensity distance covered during match-play (Thatcher and Batterham, 2004). Furthermore, Part A of the protocol incorporated 3 min static rest periods between the five 15 min exercise periods, whereas only ~43.4 static rest pauses of three seconds duration on average every two minutes are performed during matches (Reilly, 1997).

Perhaps the main limitation with the LIST as a valid simulation of match-play is that for the latter part of the test subjects are required to run to exhaustion. In contrast, soccer is a self-paced sport whereby players aim to complete a full 90 min match, therefore, due to the run to exhaustion, the total distance covered cannot be standardised. Consequently, although

the LIST may prove a useful training tool to improve and measure match fitness, its applicability as a standardised research tool is questionable.

The previously developed soccer simulations have succeeded in replicating either the physiological (Drust et al., 2000a; Nicholas et al., 2000; Thatcher and Batterham, 2004) or local muscular (Greig et al., 2006) fatigue of match-play. However, none have established both factors concurrently whilst reflecting the multidirectional nature of the sport. In light of the results from the present study and initial pilot work, the multidirectional utility movements and frequent acceleration and deceleration inherent to match-play and performed during the SAFT<sup>90</sup> may be crucial for replicating the demands of soccer. This could be due to the high physiological demands and local muscular contraction needed to perform these movements (Bangsbo, 1994).

Overall, despite either the improved ecological validity of treadmill-based protocols (Drust et al., 2000a; Thatcher and Batterham, 2004; Greig et al., 2006), or enhanced specificity of evaluation for free-running protocols (Nicholas et al., 2000), previous soccer simulations are consistently associated with methodological flaws. It was the aim of this investigation to create a soccer match-play simulation that could be standardised to closely replicate the activity profile and movements of soccer, as well as recreate the physiological responses. Therefore, in consideration of the results presented, the SAFT<sup>90</sup> may be held to accurately reflect the movement, physiological demands and nature of modern soccer. However, it should be acknowledged that the SAFT<sup>90</sup> cannot be proven as the most valid match-play simulation until the same subject population is examined for physiological and performance measures against alternate exercise protocols. This may provide a direction for future research.

It should also be considered that the SAFT<sup>90</sup>, based on English Championship level matches, was evaluated using semi-professional soccer players. Due to the difference in standard of players, it could be argued that the SAFT<sup>90</sup> would be more likely to induce greater fatigue responses for the semi-professional players. However, numerous studies have similarly investigated the physiological responses to match simulations using subjects of a lower ability than those from which the data were derived (Drust et al., 2000a; Greig et al., 2006). Furthermore, research has reported similar physiological profiles of professional English soccer players ( $VO_{2max}$ :  $61.4 \pm 3.5$  ml·kg<sup>-1</sup>·min<sup>-1</sup>; Thatcher and Batterham, 2004) compared with the semi-professional players used in the current study ( $VO_{2max}$ :  $57.6 \pm 5.1$  ml·kg<sup>-1</sup>·min<sup>-1</sup>). Therefore, present and future research findings using the SAFT<sup>90</sup> with semi-professional players should be deemed transferrable to professional players.

### **3.7. Conclusions**

The results from the present investigation suggest that the SAFT<sup>90</sup> accurately simulates the demands associated with soccer match-play. The simulation was based on, and reflects, current match-play work rates in high-level soccer whilst also replicating the movement demands of the sport by incorporating utility and multidirectional movements. The physiological responses to the SAFT<sup>90</sup> were similar to those reported in published literature from actual matches. The current data support the use of the SAFT<sup>90</sup> as a tool for soccer training and rehabilitation from injury or as an economical lab-based simulation to incur soccer-specific fatigue for future applied research investigations.



**Chapter 4. Effects of Multidirectional Soccer-specific Fatigue on  
Sprinting Kinematics: Implications for Hamstring Injury Risk.**

#### **4.1. Introduction**

Hamstring strain injuries in modern, high-level soccer players account for 12-16% of total injuries (McGregor and Rae, 1995; Hawkins et al., 2001; Woods et al., 2004; Sheppard and Hodson, 2006). On average, each hamstring injury results in 21 days training and three competitive matches missed (Woods et al., 2004). Hence, they are a cause for concern to players and coaching staff due to the significant financial and time losses involved. However, to develop more effective injury prevention strategies a detailed understanding of the mechanism of injury is essential.

Of the various non-contact injury mechanisms, sprinting is the primary mechanism responsible for 57% of all hamstring injuries in professional English soccer (Woods et al., 2004). The hamstrings are bi-artrodial muscles and undergo lengthening over two joints simultaneously during the latter part of the swing phase of the gait cycle (Stanton and Purdam, 1989). A strain injury may be most likely to occur at this point whilst the hamstrings work eccentrically to decelerate the limb and control knee extension, thus placing the muscle group under high loads in an elongated position (Verrall et al., 2001). Furthermore, players are at increased susceptibility to hamstring injury at the ends of each half of soccer matches (Woods et al., 2004). Therefore, it could be hypothesised that fatigue during the latter stages of matches may increase predisposition to hamstring injury by negatively altering the biomechanics of sprinting via changing muscle flexibility (the range in motion of a muscle about a joint) and body mechanics.

Early research has reported that reduced flexibility of the hamstring musculo-tendinous unit may cause it to be stretched beyond its ability to elongate during the latter part of the swing phase of the sprint cycle (Agre, 1985). Also at this time, decreased thigh flexion and knee

extension (an indication of reduced flexibility of the rectus femoris) may result in the lower leg being “whipped” through (Tupa et al., 1995). This may cause greater knee extension and place the hamstrings on a greater stretch later on in the cycle (Tupa et al., 1995). It has also been suggested that a common mechanism for hamstring injury during sprinting is when the body increases its forward lean to maintain or increase running speed (Orchard, 2002). This forward lean causes increased lumbar lordosis and associated anterior pelvic tilt which, due to the bi-articular nature of the hamstrings, may predispose the muscle group to injury by increasing its relative length (Hoskins and Pollard, 2005b).

Research investigating the effect of fatigue on sprinting kinematics has applied a variety of fatiguing protocols. For example, Pinniger et al. (2000) investigated the effects of fatigue induced by repeated sprints or seated leg curls on kinematics during 40 m sprints, whereas Nicol et al. (2007) investigated changes in sprint kinematics before and after a marathon. However, these protocols do not reflect the fatigue associated with soccer match-play and hence transferability of findings from previous studies (Pinniger et al., 2000; Nicol et al., 2007) to soccer players is limited. Additionally, the studies by Pinniger et al. (2000) and Nicol et al. (2007) recorded sprinting action using high-speed cameras which only allowed two dimensional footage to be recorded. This method does not consider the multi-joint and multi-plane action of muscles such as the hamstrings which may be crucial for understanding injury risk and causation.

The SAFT<sup>90</sup> developed and evaluated in the previous chapter (Chapter 3) of this thesis was based on contemporary time-motion analysis data and shown to replicate the physiological and local muscular fatigue reflective of soccer match-play. The objective of this study was

to examine the effects of the SAFT<sup>90</sup> on sprinting kinematics in relation to movement mechanics associated with hamstring injury risk.

## **4.2. Methods**

### Participants

Nine male, semi-professional soccer players (Mean  $\pm$  SD; Age: 21.3  $\pm$  2.9 yrs; Height 185.0  $\pm$  8.7cm; Body Mass 81.6  $\pm$  6.7kg) volunteered to take part in the investigation. All players were right foot dominant (defined as their preferred ‘kicking’ leg), and completed on average, two squad training sessions and two matches per week. Subjects were only included in the study if they were not injured or rehabilitating from an injury at the time of testing, and had no history of a previous hamstring injury within three months prior to testing. Ethical approval for the study was obtained in accordance with the Declaration of Helsinki and the study was approved by the Departmental Ethics Committee. Written, informed consent was obtained prior to data collection.

### Experimental Design

One week prior to testing, subjects completed a 30 min familiarisation session with the SAFT<sup>90</sup> protocol and test equipment. Prior to all testing, subjects performed a standardised warm-up procedure involving 5 min on a cycle ergometer at 60 w, followed by 5 min of static and dynamic stretches for the major lower limb muscle groups and finally 5 min light jogging. Subjects completed the SAFT<sup>90</sup> protocol in two 45 min periods, with a 15 min passive half-time period (for further details of the SAFT<sup>90</sup> protocol see Chapter 3). Subjects performed three maximum effort 10 m sprints with a 3 m running start at 0, 15, 30, 45, 46, 60, 75 and 90 min of the SAFT<sup>90</sup>, with kinematic data of one complete stride for the

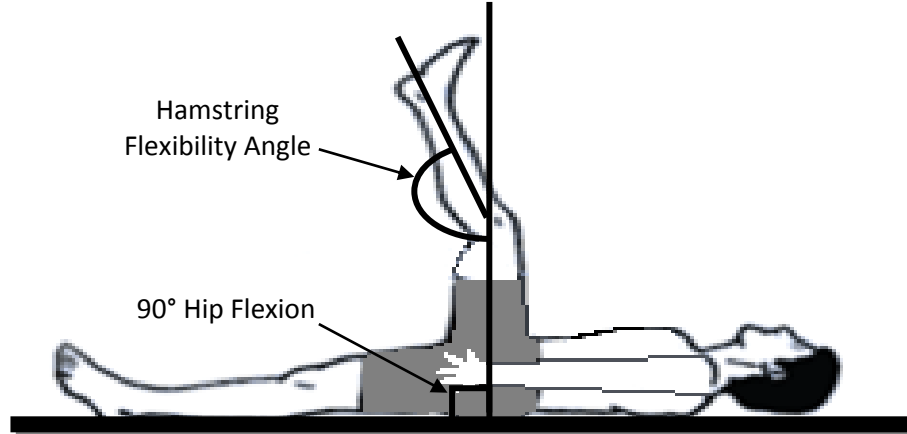
dominant leg and sprint times recorded. All testing was performed on a non-slip indoor surface.

The subjects performed no vigorous exercise 24h prior to testing, nor consumed any caffeine or alcohol. Testing was conducted at the beginning of the 2007/2008 English soccer season, with the training load and amount of match-play performed standard for the competitive season.

### Hamstring Flexibility Test

After completing the warm-up and prior to the SAFT<sup>90</sup>, hamstring muscle flexibility of the dominant leg was measured using a common clinical active range-of-motion test referred to as the “90-90” or “active knee extension” test (Harvey and Mansfield, 2000). This was performed to provide a measure of hamstring muscle flexibility pre- and post-SAFT<sup>90</sup> which could not be determined using kinematic analysis. The flexibility test was performed with the subject lying supine, flexing the hip to 90° and with 90° knee flexion and then actively extending the knee until resistance was felt (Figure 4.1). The angle of maximum knee extension was measured using a goniometer (Cranlea & Company, Bournville, United Company), with the test repeated three times in order to calculate a mean score following standard procedures (Árnason et al., 2004a). The arms of the goniometer were aligned with the greater trochanter of the femur and the lateral malleolus previously marked, and the axis of the goniometer over the lateral femoral epicondyle. The test is considered to be the most valid test of hamstring flexibility (James et al., 1998) and has an inter-rater reliability coefficient of  $r = 0.99$  in a controlled experiment (Gajdosik and Lusin, 1983). The short duration of the procedure (3x ~3 s stretch) and time it was employed within the overall testing (immediately after the warm-up) were selected as research has shown no significant

effect on 10 yard sprinting performance following an acute bout of active stretching to the lower limb muscles (Bullis et al., 2007).



**Figure 4.1.** Hamstring flexibility measurement setup

### Sprint Data Collection

Twenty-two reflective markers (25 mm spheres) were placed on selected anatomical locations to calculate motion of the pelvis (relative to the horizontal), hip and knee in the sagittal plane. Prior to testing, markers were attached bilaterally to: anterior superior iliac spines (ASIS); posterior superior iliac spines (PSIS); greater trochanters; medial and lateral femoral epicondyles (removed following static trial); four marker clusters for mid-thigh and shank; ankle medial and lateral malleoli; calcaneus; base of the fifth metatarsal; lateral border of the foot and base of the hallux. Markers were attached using double-sided adhesive tape and marker positions traced on the skin with ink to ensure dislodged markers could be replaced precisely in their original position.

Three dimensional motion analysis was carried out using 14 Proreflex infrared cameras (Qualisys, Inc. Sweden; 658x500 pixels) with the sample frequency set at 200 Hz. Along with six wall mounted cameras, eight additional cameras on 1.5 m tripods were strategically positioned around the 10 m sprint track between 4 and 12 m to ensure each

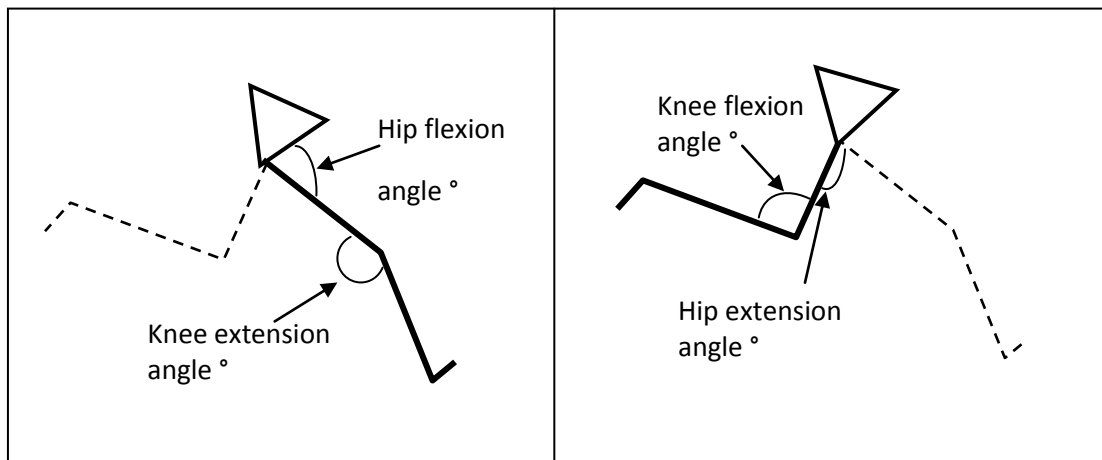
marker could be visible by at least two cameras at all times within the capture volume. Prior to data collection, the capture volume of approximately 4.5x1.1x1.5 m<sup>3</sup> was calibrated in accordance with guidelines provided by Qualisys (Qualisys, Inc. Sweden). To do so, a dynamic method was used whereby a two-marker wand of known length (749.9 mm) was moved around the capture volume while a stationary reference object, a L-frame (dimensions: 850x650 mm) containing four markers of known locations to the system, was used to define a right-handed coordinate system for motion capture.

### Sprint Protocol

Subjects performed three 10 m sprints with a 1 min rest period between every 15 min during the SAFT<sup>90</sup> to help ensure at least one successful recording of kinematic data. The 10 m distance was selected as is acknowledged to be the average distance for a sprint bout performed in modern soccer (Stolen et al., 2005; Bangsbo et al., 2006). The sprint 10 m track was marked out parallel to the SAFT<sup>90</sup> course with infrared photo-electric cells interfaced to a timing system (Newtest System, Newtest Oy, Oulu, Finland), and with a further 3 m marked out for a rolling start. To ensure subjects performed one complete dominant sprint stride within the camera capture area and at close to maximum speed without altering their stride, subjects were familiarised with the track and camera recording area during the warm-up.

The Qualisys Track Manager (QTM) software<sup>®</sup> (Qualisys, Inc. Sweden) was used to record sprint trials. A fourth-order zero-phase-shift Butterworth digital low-pass (10 Hz) filter was applied to filter out high frequency noise. Data were exported to C-motion Visual 3D software<sup>®</sup> (Visual3D, Version 2.84, C-Motion, Inc, Rockville, MD) to model the pelvis and dominant lower limb. Kinematic data on the most successful of the three sprints performed

every 15 min during the SAFT<sup>90</sup> were selected for further analysis. The most successful trial was defined as that in which all data were successfully collected within the capture area. Dependant variables were selected relating to potential associations regarding risk factors for hamstring injuries discussed previously (hamstring and rectus femoris theoretical muscle length based on joint position, pelvic tilt and lower limb segmental velocity). The dependant variables included: stride length (measured along X axis from placement of calcaneus marker of the dominant limb from touch-down to toe-off during the stride cycle), maximum shank centre of mass velocity (VCM), maximum thigh VCM, maximum hip flexion angle, maximum hip extension angle, maximum knee flexion angle, maximum knee extension angle, maximum anterior pelvic tilt angle and maximum posterior pelvic tilt angle. Additionally, a combined maximal hip flexion and knee extension angle was calculated and used to indicate hamstring length (observed during the latter part of the swing phase; Figure 4a). A combined maximum hip extension and knee flexion angle was calculated and used to indicate rectus femoris length (observed during the end of the recovery phase; Figure 4b). Averaged 10 m sprint times were also recorded.



**Figure 4.2.** Diagrammatic representation of calculations for indications of: 4.2a. Hamstring muscle length; 4.2b. Rectus femoris muscle length



## Data Analysis

Descriptive statistics of outcome measures included means and standard deviations ( $\pm$ SD). Before using parametric tests, the assumption of normality was verified using the Kolmogorov–Smirnov test. Sprint performance repeatability was assessed using the intraclass correlation coefficient (ICC) between the three sprints at each of the eight test times during the SAFT<sup>90</sup>. Differences between dependant variables at the eight time points were tested for significance employing repeated measures analyses of variance (ANOVA), with least-significant difference (LSD) post hoc tests used. Pearson correlation coefficient was calculated to investigate the relationship between sprint times and stride length. Statistical analysis was processed using SPSS statistical software (version 14.0, Chicago, IL<sup>®</sup>) with significance levels set at  $P \leq 0.05$ . Effect sizes were also calculated using the partial Eta-squared (Eta) method to estimate the magnitude of the difference between time points. When applied to ANOVA, it has been suggested that an effect size of 0.1 represents a small effect size; 0.25 a medium effect; and  $\geq 0.4$  a large effect (Portney and Watkins, 1997).

### **4.3. Results**

#### Active Hamstring flexibility

There was a significant decrease in active hamstring flexibility between pre- and post-exercise during the SAFT<sup>90</sup> (0 min:  $159.5 \pm 11.7^\circ$  vs 90 min:  $154.9 \pm 10.2^\circ$ ;  $P < 0.05$ ).

#### Sprint Times, Stride Length and Pelvic VCM

The ICC of sprint times at each of the eight time points during the SAFT<sup>90</sup> showed a high level of repeatability in sprinting performance for subjects with all values above 0.83.

There was a significant time dependent increase in sprint time of 8.18% during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.63). Sprint time significantly increased during the first half of the SAFT<sup>90</sup> by 5.54% (0 min:  $1.672 \pm 0.081$  s vs 45 min :  $1.770 \pm 0.123$  s;  $P < 0.01$ ), with a further 3.25% increase during the second half (46 min:  $1.762 \pm 0.116$  s vs 90 min:  $1.821 \pm 0.592$  s;  $P < 0.01$ ).

There was a significant difference in pelvic VCM during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.59) with post hoc tests revealing a significant decrease of 10.66% throughout the full 90 min (0 min:  $8.2 \pm 0.4$  m/s vs 90 min:  $7.3 \pm 0.4$  m/s;  $P < 0.01$ ). Significant decreases in pelvic VCM were observed during the first half (0 min:  $8.2 \pm 0.4$  m/s vs 45 min:  $7.6 \pm 0.3$  m/s;  $P < 0.01$ ) and second half (46 min:  $7.6 \pm 0.4$  m/s vs 90 min:  $7.3 \pm 0.4$  m/s;  $P < 0.01$ ) of the SAFT<sup>90</sup> by 7.30 and 4.00%, respectively. Pelvic VCM was not significantly different between immediately before and after half-time (45 min:  $7.6 \pm 0.3$  m/s vs 46 min:  $7.6 \pm 0.2$  m/s;  $P > 0.05$ ).

Stride length significantly decreased by 17% during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.51). Post hoc tests identified significant decreases during the first half (0 min:  $4.04 \pm 0.35$  m vs 45 min:  $3.65 \pm 0.32$  m;  $P < 0.05$ ) and second half after 60 min (60 min:  $3.86 \pm 0.39$  m vs 90 min:  $3.55 \pm 0.56$  m;  $P < 0.05$ ). There was a significant correlation between stride length and sprint time (correlation coefficient = 0.933;  $P < 0.01$ ).

### Kinematic Parameters

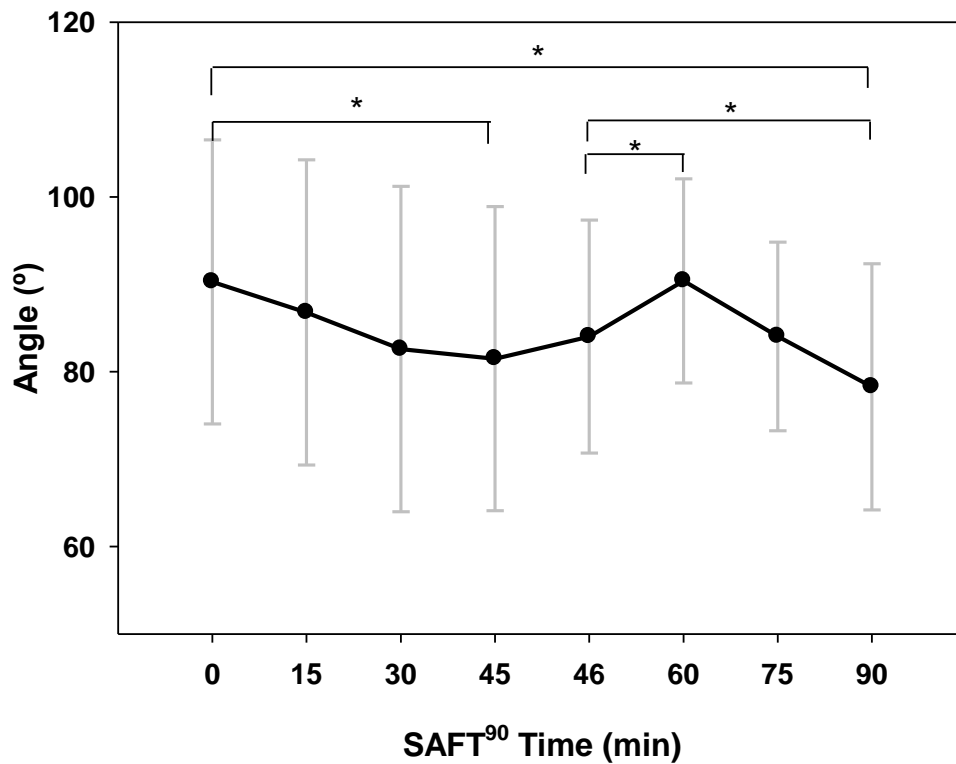
Hip range-of-motion indicated a shift from a more flexed to extended position with fatigue during the SAFT<sup>90</sup>. There was a significant difference in maximum hip flexion angle with fatigue ( $P < 0.01$ ; Partial Eta squared = 0.33). The post hoc test identified a significant reduction in maximum hip flexion angle between 0 and 90 min of the fatiguing protocol (0

min:  $81.5 \pm 3.3$  °; 45 min:  $73.3 \pm 4.0$  °; 90 min:  $68.6 \pm 4.4$  °;  $P < 0.05$ ). Maximum hip extension angle was also significantly affected by fatigue during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.35), showing a significantly greater maximum hip extension angle after each half, respectively (0 min:  $-8.5 \pm 2.7$  ° vs 45 min:  $-14.8 \pm 3.0$  °;  $P < 0.05$ ; 46 min:  $-10.5 \pm 1.0$  ° vs 90 min:  $-15.3 \pm 1.4$  °;  $P < 0.05$ ).

There was a shift towards a more flexed position for knee joint range-of-motion with fatigue during the SAFT<sup>90</sup>. A significant difference was observed in maximum knee extension angle with fatigue ( $P < 0.01$ ; Partial Eta squared = 0.37) with a significant decrease in range observed during the full 90 min (0 min:  $8.7 \pm 2.8$  ° vs 90 min:  $20.9 \pm 3.6$  °;  $P < 0.01$ ). Post hoc tests identified a significant decrease in maximum knee extension angle during the first half of the SAFT<sup>90</sup> (0 min:  $8.7 \pm 2.8$  ° vs 45 min:  $19.9 \pm 3.8$  °;  $P < 0.05$ ). A further decrease was observed during the second half (46 min:  $13.6 \pm 2.7$  ° vs 90 min:  $20.9 \pm 3.6$  °) although this finding was not statistically significant ( $P = 0.106$ ). Maximum knee flexion angle also revealed a significant difference with fatigue during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.32). However, despite a trend of increased maximum knee flexion angle observed during each half of the SAFT<sup>90</sup> (0 min:  $121.5$  °  $\pm$  6.1 vs 45 min:  $125.2 \pm 5.7$  °; 46 min:  $119.9 \pm 6.1$  vs 90 min:  $123.1 \pm 6.1$  °), these findings were not statistically significant ( $P = 0.06$ ;  $P = 0.15$ ).

Combined maximal hip flexion and knee extension angle revealed a significant time dependent difference during the SAFT<sup>90</sup> ( $P < 0.05$ ; Partial Eta squared = 0.49; Figure 4.3). Post hoc tests identified a significant decrease in the combined angle during each half, respectively (0 min:  $222.4 \pm 2.5$  ° vs 45 min:  $211.8 \pm 2.0$  °;  $P < 0.05$ ; 46 min:  $213.9 \pm 2.5$  ° vs 90 min:  $195.5 \pm 7.8$  °;  $P < 0.05$ ). A significant increase in combined maximal hip flexion

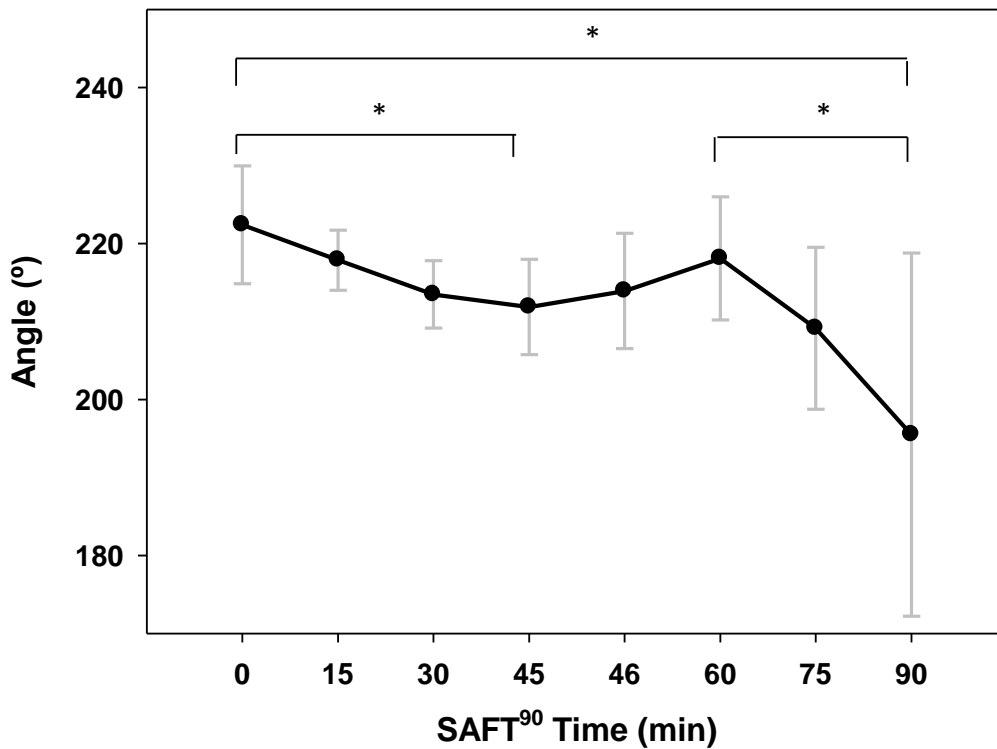
and knee extension angle was observed between the first 15 min following the half-time interval (46 min:  $213.9 \pm 2.5^\circ$  vs 60 min:  $218.1 \pm 2.6^\circ$ ;  $P < 0.05$ ).



**Figure 4.3.** Combined maximal hip flexion and knee extension angle during SAFT<sup>90</sup>

\*Significant difference between time points ( $P < 0.05$ )

Combined maximal hip extension and knee flexion angle revealed a significant effect of fatigue over time during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.38; Figure 4.4). A significant increase was observed during the first half of the fatiguing protocol (0 min:  $90.3 \pm 5.4^\circ$  vs 45 min:  $81.5 \pm 5.8^\circ$ ;  $P < 0.05$ ), with a further increase during the second half after 60 min (60 min:  $90.4 \pm 4.0^\circ$  vs 90 min:  $78.3 \pm 4.7^\circ$ ;  $P < 0.05$ ).



**Figure 4.4.** Combined maximum hip extension and knee flexion angle during SAFT<sup>90</sup>

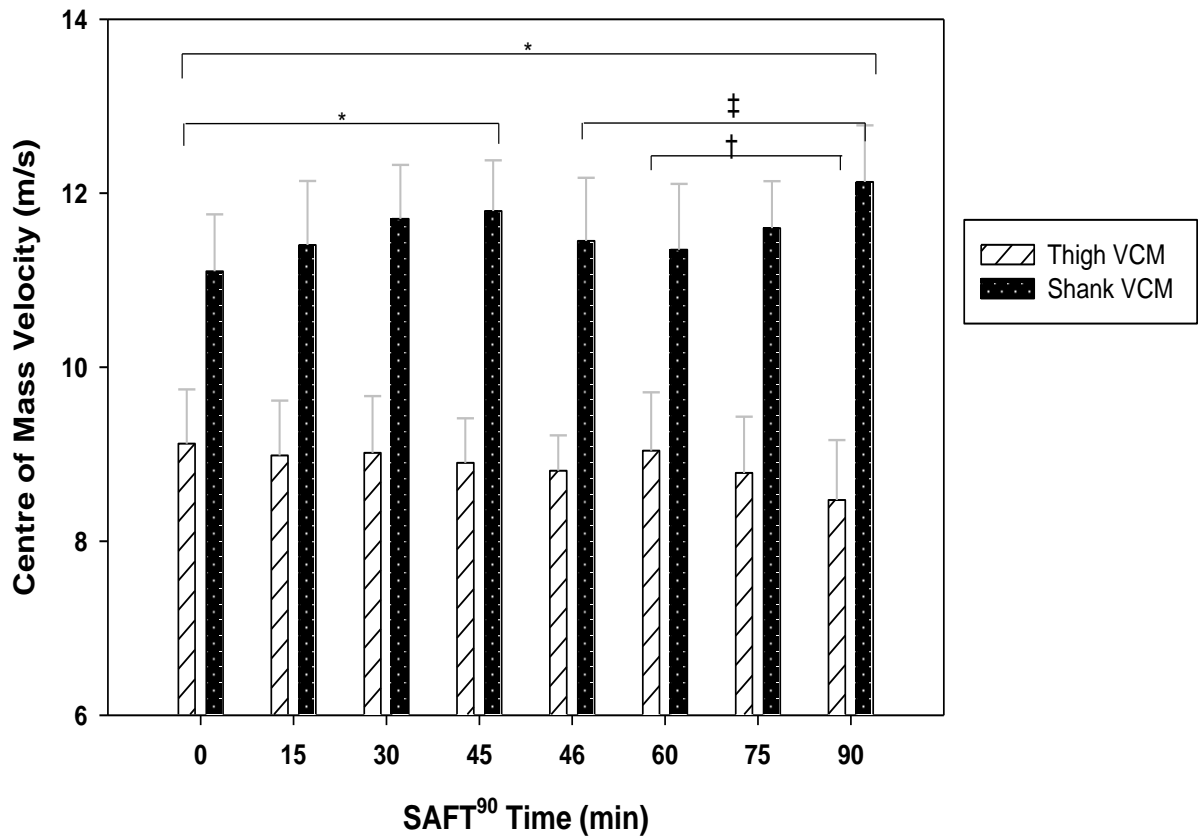
\*Significant difference between time points ( $P < 0.05$ )

There was a significant difference in maximum anterior pelvic tilt angle during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.54). Post hoc tests identified significant increases in maximum anterior pelvic angle during each half, respectively (0 min:  $-15.7 \pm 1.1$  vs 45 min:  $-18.8 \pm 5.4$  °;  $P < 0.05$ ; 46 min:  $-18.1 \pm 1.8$  vs 90 min:  $-20.8 \pm 1.9$  °;  $P < 0.05$ ). There was no significant change in maximum posterior pelvic tilt angle during the SAFT<sup>90</sup> ( $P > 0.05$ ). However, a general trend towards decreased maximum posterior pelvic tilt angle was observed over time (0 min:  $-30.1 \pm 3.1$  vs 90 min:  $-27.7 \pm 1.9$ ).

#### Lower Limb Segmental Centre of Mass Velocities (VCM)

A significant difference was observed during the SAFT<sup>90</sup> for both maximum thigh VCM ( $P < 0.01$ ; Partial Eta squared = 0.43) and shank VCM ( $P < 0.01$ ; Partial Eta squared = 0.93;

Figure 4.5). A significant decrease in maximum thigh VCM was observed during the first half (0 min:  $9.1 \pm 0.2$  m/s vs 45 min:  $8.9 \pm 0.2$  m/s;  $P < 0.05$ ), and second half after 60 min (60 min:  $9.0 \pm 0.2$  m/s vs 90 min:  $8.5 \pm 2.3$  m/s;  $P < 0.05$ ). Post hoc tests for maximum shank VCM identified a significant increase during each half of the SAFT<sup>90</sup>, respectively (0 min:  $11.1 \pm 0.6$  vs 45 min:  $11.8 \pm 0.6$  m/s;  $P < 0.01$ ; 46 min:  $11.5 \pm 0.8$  vs 90 min:  $12.1 \pm 0.6$  m/s;  $P < 0.01$ ).



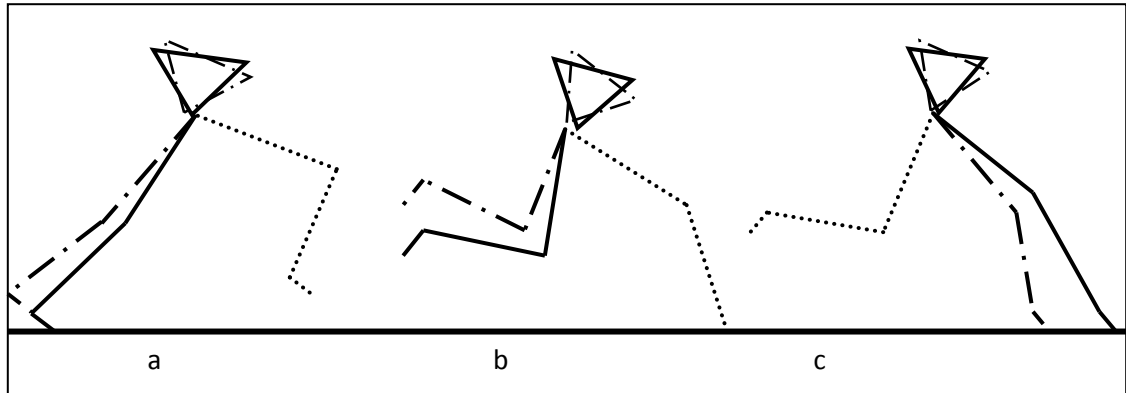
**Figure 4.5.** Maximum thigh and shank VCM during SAFT<sup>90</sup>

\*Significant difference in both thigh and shank VCM between time points ( $P < 0.05$ )

‡Significant difference in shank VCM between time points ( $P < 0.01$ )

†Significant difference in thigh VCM between time points ( $P < 0.05$ )

Overall, the results indicated a time dependent alteration in sprinting kinematics with fatigue during the SAFT<sup>90</sup> (Figure 4.6).



**Figure 4.6.** Schematic representation of dominant leg sprinting stride comparison between non-fatigued and fatigued condition. a = take-off. b = recovery part of swing phase. c = end of swing phase/initial contact.

Non-fatigued: ——— Fatigued: - · - Neutral, non-dominant leg: ·······

#### 4.4. Discussion

The present study investigated the effect of the SAFT<sup>90</sup> on sprint performance and lower limb kinematics. A relationship was observed between increased sprint time and reduced stride length throughout the 90 min soccer simulation. The reduced sprint performance observed towards the final stages of the SAFT<sup>90</sup> concurs with previous findings by Krustup et al. (2006) following an actual soccer match. The authors attributed the decline in sprint performance to reduced glycogen levels in individual muscle fibres (Krustup et al., 2006). Findings from the present study may provide a mechanical explanation for the slower sprint times with fatigue, related to altered sprint kinematics which may have caused shorter stride lengths.

The temporal pattern of reduced sprint ability during the latter stages of the SAFT<sup>90</sup> may relate to the temporal pattern of hamstring injuries during matches (Woods et al., 2004). Evidence suggests that reduced hamstring length with fatigue may be a risk factor for injury by causing the hamstrings to be stretched beyond their ability to elongate (Agre, 1985). Thus, reduced hamstring flexibility during fatigued sprinting may contribute to increased predisposition to hamstring injury during the latter stages of soccer matches. In relation to technique, it was theorised that there would be a reduction in combined maximum hip flexion and knee extension angle (used to indicate hamstring muscle length) and stride length towards the end of each half of the simulation. Findings of the present study confirmed this theory which concurs with previous research using non-soccer-specific fatiguing protocols (Tupa et al., 1995; Pinniger et al., 2000; Hanon et al., 2005; Nicol et al., 2007). This may indicate physiological contracture of the hamstring musculo-tendinous unit with fatigue to increase risk of strain injury.

In further regard to hamstring range-of-motion, a decrease in maximum knee extension angle was observed with fatigue during the SAFT<sup>90</sup>. This finding contradicts research by Pinniger et al. (2000) who argued that increased knee extension may be the result of reduced ability of the fatigued hamstrings to limit the end point of forward leg motion (Pinniger et al., 2000). However, the fatiguing protocols administered by Pinniger et al. (2000) involved either performing hamstring curls on an isokinetic dynamometer or repeated sprints, thus inducing more acute fatigue unreflective of soccer match-play.

Range of motion and flexibility of the quadriceps muscle group may also play a role in hamstring injury risk during sprinting. In the present investigation, a significant increase in combined maximum hip extension and knee flexion angle, indicating increased rectus



femoris length, was observed at the start of the swing phase of sprinting during the latter stages of each half of the SAFT<sup>90</sup>. Although this finding contradicts previous research by Sprague and Mann (1983), the study was carried out in 1983, with subsequent advances in technology to study three dimensional aspects of technique considered more reliable (Zhang and Hsiang, 2008). Furthermore, findings from the present investigation also showed a significant increase in maximum shank segmental velocity at the ends of each half of the SAFT<sup>90</sup>. This may lend support to the increased maximum hip extension and knee flexion angle with fatigue observed, and suggest increased passive elastic recoil of the rectus femoris tendon (Gabbe et al., 2006). This increased shank segmental velocity could create additional strain on the hamstring musculo-tendinous unit at the end of the swing phase of the sprint cycle and consequently create extra demand on the hamstring muscles to eccentrically decelerate the shank forward momentum. Research has reported decreased eccentric hamstring strength with fatigue associated with soccer match-play (Rahnama et al., 2003; Greig, 2008), thus potentially impairing the ability of the hamstrings to decelerate the limb effectively and avoid injury.

Altered body mechanics regarding pelvic tilt may also contribute to hamstring injury risk. Kinematic results revealed a significant increase in maximum anterior pelvic tilt angle with fatigue during the SAFT<sup>90</sup>. This may be associated with increased lumbar lordosis, which is common in sports involving kicking actions as a result of over-development of the psoas muscles used in kicking (Rasch and Burke, 1978). In relation to the sprinting technique, increased forward lean of the body associated with greater anterior pelvic tilt may predispose the bi-articular hamstrings to injury by increasing their relative length (Hoskins and Pollard, 2005b). This technique alteration could be an attempt to maintain sprint performance by increasing the hamstrings range-of-motion and stride length. However, this

compensatory mechanism may conversely create an additional strain on the muscle group, thereby increasing risk of injury (Watson, 1995).

The alterations in sprinting kinematics with fatigue were primarily observed immediately prior to the end of each half of the soccer simulation. However, a similar performance impairment and sprint technique alteration was also observed immediately after the 15 min half-time interval. Interestingly, at 60 min during the SAFT<sup>90</sup> players showed an improvement in sprinting performance and a recovery towards non-fatigued sprinting technique as demonstrated during the start of the first half of the simulation. This may suggest that players are at a similar risk of hamstring injury when sprinting immediately after half-time due to a sustained 15 min period of inactivity as they are at the ends of each half due to fatigue. In support of this, an increased amount of injuries sustained has been observed immediately following half-time during soccer matches (Rahnama et al., 2002). Furthermore, Greig (2008) reported reduced eccentric hamstring strength immediately after half-time during a 90 min football-specific treadmill protocol than prior to the 15 min interval. Considering the well acknowledged relationship between reduced eccentric hamstring strength and increased hamstring injury risk, findings by Greig (2008) along with those from the present investigation would support the theory of increased hamstring injury risk at the beginning of the second half of soccer matches.

Research investigating performance following half-time (Mohr et al., 2004) has reported impaired sprint performance prior to the start of the second half of a friendly soccer match. This was attributed to a lowered muscle temperature, which may have caused reduced muscle flexibility and thus increased risk of musculo-tendinous injury (Mohr et al., 2004). Following a moderate-intensity, half-time, re-warm-up intervention strategy administered

by Mohr et al. (2004) there was no lowered muscle temperature or deterioration in sprint performance observed. This may give support for further investigation into half-time re-warm-up strategies, not only to improve early second half performance but also to reduce injury risk. Such strategies could involve a dynamic stretching routine to increase muscle blood flow, facilitate motor control and coordination, and increase core and peripheral temperature to increase muscle flexibility (Little and Williams, 2006).

Regarding study limitations, it could be considered that the repeated sprint routine performed in the present investigation at 15 min intervals during the SAFT<sup>90</sup> may itself have caused impaired sprinting performance irrespective of completing the fatiguing soccer simulation. Furthermore, with no control group monitored over same time period this theory cannot be disproved. However, results from the pilot study in chapter 3 observed no significant impairment in sprinting performance during a 90 min intermittent treadmill protocol using an identical sprint testing routine. Therefore, current findings would suggest that the added demands of performing multidirectional utility movements in the SAFT<sup>90</sup> may have been crucial at impairing sprinting performance reflective of match-play (Krustrup et al., 2003).

Findings from the present investigation are based on accurate data collection during the testing procedures; however, markers occasionally became detached during the 90 min soccer simulation. Although these were replaced as precisely as possible using the marked positions on the skin, this limitation should be considered. Furthermore, although hamstring and rectus femoris muscle lengths were indicated using a combined hip and knee angle calculation, these are not measurements of actual muscle length or flexibility. Therefore, a

direction for future investigation could be to examine changes in hamstring muscle flexibility using computer modelling during soccer-specific fatigue.

#### **4.5. Conclusions**

Findings from the present investigation indicate that exercise simulating the demands of soccer match-play produced a time dependant alteration in sprinting kinematics. The SAFT<sup>90</sup> resulted in impaired sprinting performance during the latter stages of each half of the soccer simulation, and also immediately following the half-time interval. Furthermore, decreased hamstring length during the late swing phase of the sprinting cycle was indicated during fatigued sprinting. This, combined with increased lower limb segmental velocity potentially due to elastic recoil from the increased rectus femoris length observed earlier on in the stride cycle and increased anterior tilted pelvis with fatigue may increase strain on the hamstrings. These new insights into the primary mechanism for hamstring injury may help explain increased predisposition to hamstring strains during the latter stages of soccer matches and provide a good knowledge base to develop injury prevention strategies.

**Chapter 5. Effects of Multidirectional Soccer-specific Fatigue on  
Markers of Hamstring Injury Risk.**

## **5.1. Introduction**

Epidemiological research into professional soccer in the 1980's reported a majority of ankle and knee ligament injuries (Ekstrand and Gillquist, 1983a; Nielsen and Yde, 1989; Sandelin et al., 1985), while more recent studies have documented an increased proportion of hamstring strain injuries; now reported as the most common injury to players (Árnason et al., 1996, 2004a; Hawkins and Fuller, 1999; Woods et al., 2004). The English FA revealed that 2378 professional players missed a total of 13116 days and 2029 competitive matches over two soccer seasons due solely to hamstring injuries (Woods et al., 2004), causing considerable pain and disability for athletes. To minimise the prevalence of hamstring injuries and the associated costs, more effective injury preventive intervention programmes are needed (Rahnama et al., 2002). Such strategies should be based on altering aetiological risk factors for injury (Rahnama et al., 2002).

The most commonly suggested aetiological risk factors for hamstring strain injury are: insufficient flexibility (Hartig and Hendersen, 1994; Worrell et al., 2001; Witvrouw et al., 2003), inadequate warm-up (Safran et al., 1988; Cross and Worrell, 1999), muscle weakness (Jönhagen et al., 1994; Orchard et al., 1997; Croisier et al., 2002), strength imbalance between quadriceps and hamstring muscles (Orchard et al., 1997; Croisier et al., 2002), fatigue (Mair et al., 1996; Rahnama et al., 2002, 2003) and previous injury (Orchard, 2001; Verrall et al., 2001). Although injury may occur due to a single factor, it is more likely to be the result of an interaction between multiple risk factors (Hoskins and Pollard, 2005a). The interaction between fatigue and hamstring muscular strength may be crucial for injury risk.

Muscular fatigue manifests during soccer match-play, and is most evident towards the end of play. A 5-10% decrease in overall distance covered has been observed during the second half of matches (Bangsbo et al., 1991; Mohr et al., 2003), most notably through a reduction in medium (Di Salvo et al., 2007) and high intensity activity (Mohr et al., 2003). Furthermore, almost half of all hamstring injuries are sustained during the last 15 min of each half of matches (Woods et al., 2004). Therefore, evidence suggests that fatigue may be a predisposing factor to hamstring strain injury.

As a result of fatigue, muscular strength deficiency has been proposed to increase susceptibility to hamstring injury (Rahnama et al., 2003; Greig, 2008). Decreased hamstring strength due to fatigue may reduce a muscles force absorption capabilities, therefore increasing the potential for injury (Garrett, 1996). Specifically, injury risk may be greatest with muscle weakness during eccentric contractions, as fatigued muscles are more susceptible to strain whilst eccentrically contracting (Mair et al., 1996).

Rahnama and colleagues (2003) examined the relationship between muscular strength imbalances and fatigue using a 90 min intermittent treadmill protocol based on work rates of professional soccer players. Isokinetic strength for concentric and eccentric knee flexion and extension were assessed before exercise, at half-time and immediately post-exercise. The results showed significant reductions in knee flexor and extensor peak torque, and a reduced functional eccentric hamstrings:concentric quadriceps (eccH:conQ) ratio after 90 min. This may imply insufficient hamstring strength to counteract the force produced by the quadriceps muscle group, and thus impair the ability of the hamstrings to decelerate lower limb motion during the late swing phase of sprinting. At this point eccentric overload of the hamstrings could cause a strain injury (Garrett, 1990).

The exercise protocol employed by Rahnama et al. (2003) although physiologically reflective of match-play demands, may not accurately replicate the activity profile of soccer due to the low frequency of speed change (92 changes per 90 min; Greig, 2008). In light of this, Greig et al. (2006) developed a more intermittent (1170 changes per 90 min) treadmill protocol reflective of the activity profile of recent match-play data to investigate changes in lower limb muscular strength (Greig, 2008). Ten male professional soccer players completed the exercise protocol, each performing isokinetic dynamometry testing to assess knee flexion and extension peak torque at 15 min intervals throughout the simulation. Results indicated a significant decrease in eccentric hamstring strength and functional eccH:conQ ratio towards the end of each half of the exercise protocol. This finding supports results by Rahnama et al. (2003) and may suggest that strength deterioration is not dependant on activity profile but on 90 min activity. The deterioration in eccentric hamstring strength and functional ratio were suggested by Greig (2008) to imply increased risk of hamstring strain injury in relation to the temporal pattern of injury incidence during matches (Woods et al., 2004).

At present, the work by Rahnama et al. (2003) and Greig (2008) are the closest attempts at investigating the effect of soccer-specific fatigue on hamstring strength and muscular imbalance. However, the previous investigations have simulated either the activity profile (Greig, 2008) or physiological demands (Rahnama et al., 2002) of soccer but not both. Furthermore, the protocols employed do not reflect the multidirectional nature and demands of the sport. Both protocols were performed in a linear gait pattern on motorised treadmills, consequently inhibiting the ability to perform multidirectional utility movements. Due to the anatomical attachments of the hamstrings, they create rotational movements at the knee



(Agre, 1985) and thus it could be postulated that utility movements cause greater stress and strain on the muscles to increase risk of injury.

The investigations by Rahnama et al. (2003) and Greig (2008) also quantified peak torque during simulated soccer match-play. However, there have been no previous data concurrently examining changes in the angle at which peak torque is attained. Brockett et al. (2001) identified a potential relationship between changes in the optimum angle for peak torque generation and increased susceptibility to muscle damage. Theoretically, such changes in the angle of peak torque may also apply to the hamstring muscles and thus have further implications for hamstring injury risk. Therefore, the aim of this study was to investigate the effect of the SAFT<sup>00</sup> on eccentric hamstring strength, hamstring:quadriceps strength imbalances, and the angles of peak torque.

## **5.2. Methods**

### Participants

Sixteen male semi-professional soccer players (Mean  $\pm$  SD; Age: 21.3  $\pm$  2.9 yrs; Height 185.0  $\pm$  8.7cm; Body Mass 81.6  $\pm$  6.7kg) were recruited to take part in the investigation. Subjects were included in the study if they were not injured or rehabilitating from an injury at the time of testing, and did not have a history of a previous hamstring injury within three months prior to testing. Written, informed consent was obtained prior to data collection from the subjects, and ethical approval for the study obtained in accordance with the Departmental and University ethical procedures.

The subjects performed no vigorous exercise 24h prior to testing, nor consumed any caffeine or alcohol. Testing was conducted at the start of the 2007/2008 English competitive soccer season, with a standard two training sessions and matches per week.

### Experimental Design

Subjects completed the SAFT<sup>90</sup> protocol, divided into two 45 min periods interceded by a 15 min passive half-time (see Chapter 3). Prior to testing, subjects completed a standardised warm-up procedure; 5 min on a cycle ergometer at 60 watt, 5 min static and dynamic stretches for the major lower limb muscle groups and 5 min light jogging and familiarisation with the SAFT<sup>90</sup>. Pre-exercise ( $t_0$ ), at half-time ( $t_{45}$ ) and post-exercise ( $t_{105}$ ), subjects performed three maximal dominant limb isokinetic contractions of concentric (conH) and eccentric knee flexion (eccH) and concentric knee extension (conQ).

### Muscle Strength Profiling

Isokinetic peak torque for the knee flexors and extensors (of the subjects' dominant leg; their 'kicking' leg) was measured using an isokinetic dynamometer (Biodex System 3, Biodex Medical, Shirley, NY). This equipment provides mechanically reliable and valid measures of torque, position and velocity on repeated trials performed on the same day as well as on different days (Drouin et al., 2004).

During testing, subjects were seated on the dynamometer in an adjustable chair with straps secured across their shoulders, chest, hips and dominant thigh to stabilise their body. The cuff of the dynamometer's lever arm was attached to the subjects' ankle just proximal to the malleolus. The axis of rotation of the dynamometer shaft was aligned with the axis of rotation of the knee joint (the mid-point between the lateral condyle of the tibia and the lateral condyle of the femur). Test positions were recorded and repeated for each subject to be used for subsequent trials.

Subjects were instructed to grasp the handle bars adjacent to the chair before performing two practice sub-maximal knee flexion and extension movements. After a brief rest,

subjects then performed three maximal voluntary concentric knee flexion and extension actions, and three eccentric knee extension actions. A one min passive recovery was allowed between each trial, with the test order standardised for subsequent trials throughout the SAFT<sup>90</sup> (at  $t_{45}$  and  $t_{105}$ ). All actions were performed through a range of 0° to 90° knee flexion and extension (0° being full extension) and at an isokinetic angular velocity of 2.09 rad·s<sup>-1</sup> (120°·s<sup>-1</sup>). Only one test speed was used to avoid inducing additional fatigue with subsequent contractions. The speed selected has been shown to be one of the fastest and safest speeds to reliably test eccentric knee flexor contractions in males (Rahnama et al., 2003), with reduced reproducibility at higher speeds ( $\geq 300^\circ\text{s}^{-1}$ ) (Drouin et al., 2004).

### Data Analysis

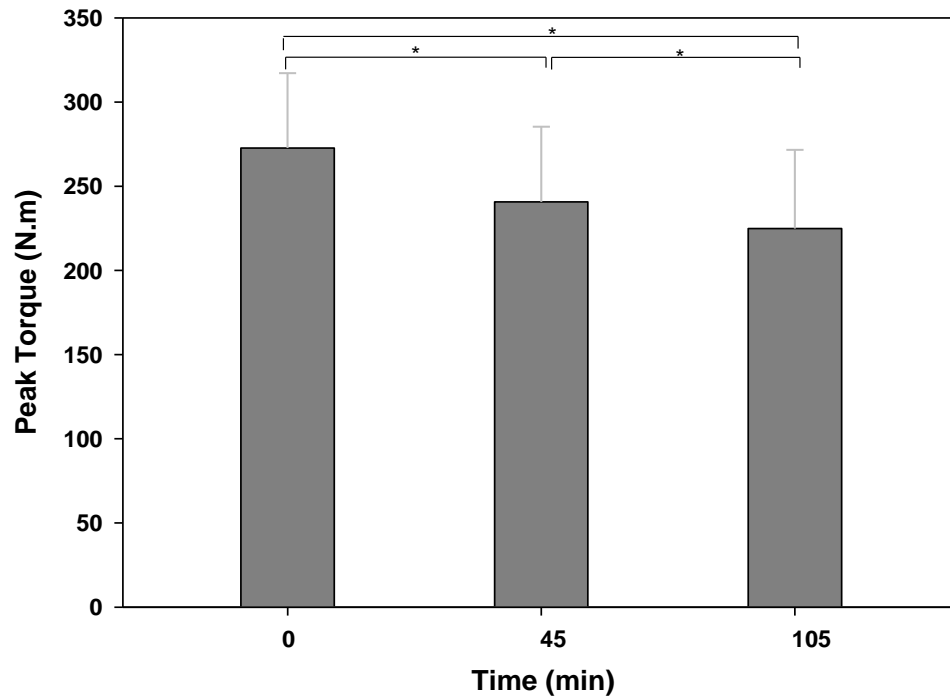
Gravity-corrected peak torque and angle of peak torque values were extracted from the strength indices. Mean peak torque values were then calculated from the three attempts following standard procedures (Rahnama et al., 2003). ConQ peak torque (PT), conH PT, eccH PT, the traditional concentric hamstrings:concentric quadriceps (conH:conQ) ratio, the functional eccH:conQ ratio, conQ angle of peak torque (APT), conH APT and eccH APT were attained. All variables were analysed in respect to changes over time throughout the SAFT<sup>90</sup>, for differences between values at the three time points: prior-to exercise ( $t_0$ ), at half-time ( $t_{45}$ ) and post-exercise ( $t_{105}$ ). Before using parametric tests, the assumption of normality was verified using the Kolmogorov–Smirnov test. An analysis of variance (ANOVA) for repeated measures, with the least significant difference (LSD) post-hoc test was used to compare means and  $\pm$ SD from muscle strength variables measured. Analysis of the data was processed using SPSS statistical software (version 14.0 Chicago, IL©) with significance levels set at  $P \leq 0.05$ . Effect sizes were determined using the partial Eta-squared method previously described in chapter 4.

### 5.3. Results

#### Quadriceps and Hamstring Peak Torque (PT)

The conQ PT was not significantly different ( $P > 0.05$ ; Partial Eta squared = 0.12) throughout the SAFT<sup>90</sup> ( $t_0$ :  $235.0 \pm 20.1$  N·m;  $t_{45}$ :  $225.0 \pm 22.4$  N·m;  $t_{105}$ :  $228.1 \pm 18.5$  N·m). There was a decrease in conH PT throughout the SAFT<sup>90</sup> which almost met the accepted level of statistical significance ( $t_0 = 140.8 \pm 38.0$ ;  $t_{45} = 133.9 \pm 27.9$ ;  $t_{105} = 131.4 \pm 20.8$  N·m;  $P = 0.052$ ; Partial Eta squared = 0.05).

There was a significant difference in eccH PT during the SAFT<sup>90</sup> ( $P < 0.01$ ; Partial Eta squared = 0.67; Figure 5.1). Post hoc tests revealed significant reductions in eccH PT between  $t_0$  and  $t_{45}$  by 5.2% ( $t_0$ :  $272.0 \pm 43.2$  vs  $t_{45}$ :  $240.4 \pm 43.2$  N·m;  $P < 0.01$ ), and also during the second half between  $t_{45}$  and  $t_{105}$  by 6.2% ( $t_{45}$ :  $240.4 \pm 43.2$  vs  $t_{105}$ :  $226.3 \pm 45.7$ ;  $P < 0.05$ ) with a 16.8% reduction over the full 90 min match simulation ( $P < 0.01$ ).

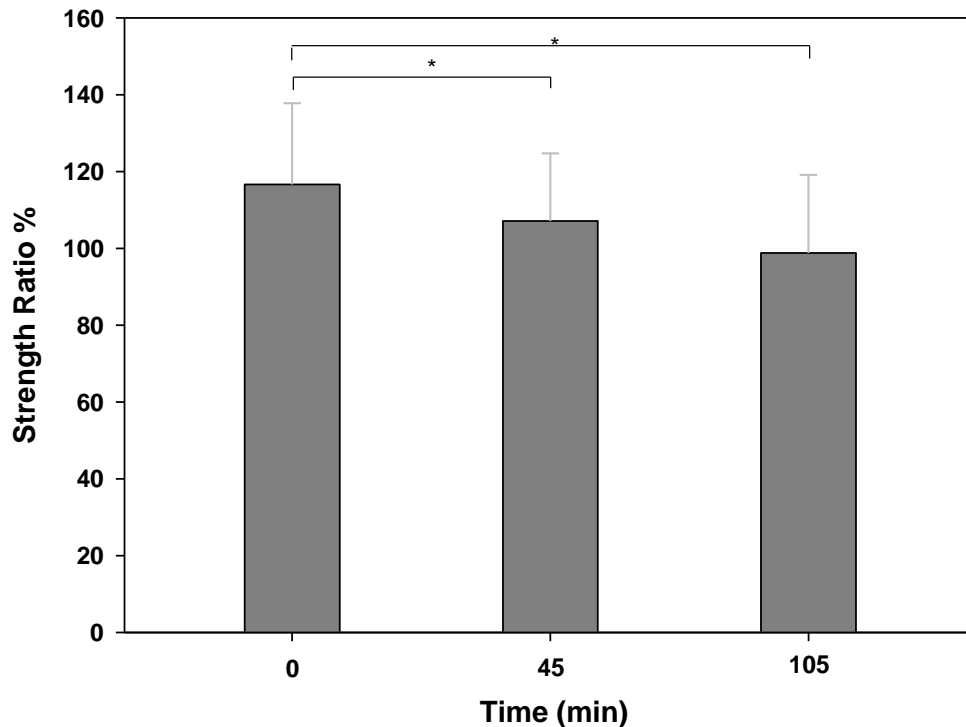


**Figure 5.1.** Eccentric hamstring peak torque during SAFT<sup>90</sup>

\*Significant difference between time points ( $P < 0.05$ )

### Traditional and Functional Muscle Strength Ratios

The traditional conQ:conH ratio revealed no significant changes during the SAFT<sup>90</sup> ( $t_0 = 59.8 \pm 15.9$ ;  $t_{45} = 60.4 \pm 11.5$ ;  $t_{105} = 57.8 \pm 9.9$  %,  $P > 0.05$ ; Partial Eta squared = 0.03). However, significant changes were observed in the functional eccH:conQ ratio ( $P < 0.05$ ; Partial Eta squared = 0.40; Figure 5.2). Post hoc tests showed a significant decrease between  $t_0$  and  $t_{45}$  by 8.9% ( $t_0 = 116.6 \pm 21.2$  vs  $t_{45} = 107.1 \pm 17.6$  %;  $P < 0.05$ ), with a 15.0% decrease over the 90 min ( $t_0 = 116.6 \pm 21.2$  vs  $t_{105} = 98.8 \pm 20.3$  %;  $P < 0.01$ ). A decrease was also observed in the eccH:conQ ratio between  $t_{45}$  and  $t_{105}$  which almost met the level of accepted statistical significance ( $t_{45} = 107.1 \pm 17.6$  vs  $t_{105} = 98.8 \pm 20.3$  %;  $P = 0.051$ ).



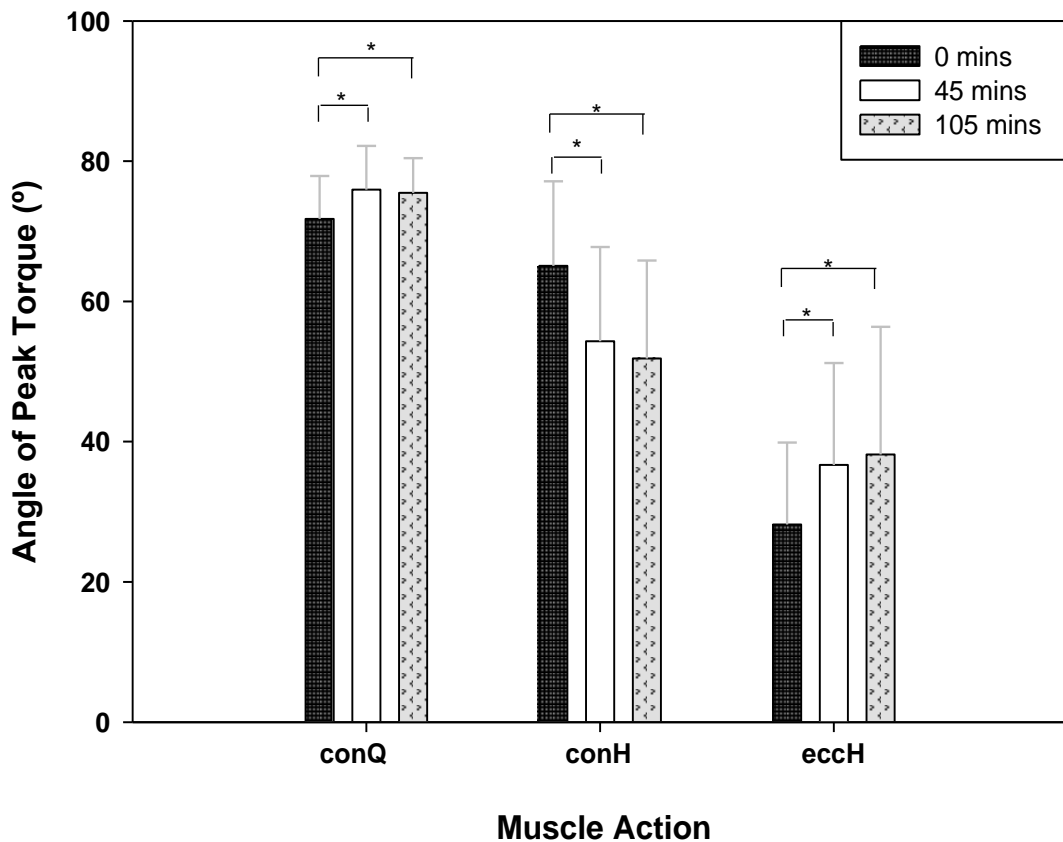
**Figure 5.2.** Eccentric hamstring:concentric quadriceps strength ratio during SAFT<sup>90</sup>

\*Significant difference between time points ( $P < 0.05$ )

### Angle of Peak Torque

There were significant differences in the conQ APT during the SAFT<sup>90</sup> ( $P < 0.05$ ; Partial Eta squared = 0.21; Figure 5.3). Significant increases were observed between  $t_0$  and  $t_{45}$  ( $t_0 =$

71.8 ± 6.1 vs t<sub>45</sub> = 75.9 ± 6.2 °; *P* < 0.01) and between t<sub>0</sub> and t<sub>105</sub> (t<sub>0</sub> = 71.8 ± 6.1 vs t<sub>105</sub> = 75.5 ± 4.91 °; *P* < 0.05). The conH APT revealed significant differences during the SAFT<sup>90</sup> (*P* < 0.01; Partial Eta squared = 0.30; Figure 5.3). Post hoc tests showed significant decreases between t<sub>0</sub> and t<sub>45</sub> (t<sub>0</sub> = 65.1 ± 12.1 vs t<sub>45</sub> = 54.3 ± 13.5 °; *P* < 0.05) and between t<sub>0</sub> and t<sub>105</sub> (t<sub>0</sub> = 65.1 ± 12.1 vs t<sub>105</sub> = 51.9 ± 14.0 °; *P* < 0.01). Significant differences were also observed in eccH APT during the SAFT<sup>90</sup> (*P* < 0.05; Partial Eta squared = 0.23; Figure 5.3). Post hoc tests identified significant increases between t<sub>0</sub> and t<sub>45</sub> (t<sub>0</sub> = 28.2 ± 11.7 vs t<sub>45</sub> = 36.7 ± 14.5 °; *P* < 0.05) and between t<sub>0</sub> and t<sub>105</sub> (t<sub>0</sub> = 28.2 ± 11.7 vs t<sub>105</sub> = 38.2 ± 18.2 °; *P* < 0.05). No significant differences in APT were observed between t<sub>45</sub> and t<sub>105</sub> for any of the muscle actions tested (*P* > 0.05).



**Figure 5.3.** Angle of peak torque for concentric quadriceps, concentric hamstring and eccentric hamstring muscle actions during SAFT<sup>90</sup>

\*Significant difference between time points (*P* < 0.05)

## 5.4. Discussion

The aim of the study was to investigate the effect of soccer match-play demands on eccentric hamstring strength, hamstring:quadriceps strength imbalances, and the angles of peak torque. The findings showed a 16.8% reduction in eccentric hamstring peak torque by the end of the 90 min multidirectional soccer simulation compared with pre-exercise values. This concurs with an identical decrement reported by Rahnama et al. (2003) testing at  $120^{\circ}\text{s}^{-1}$  angular velocity. Furthermore, the results in this chapter showed a 15.0% reduction in the functional eccH:conQ strength ratio during the SAFT<sup>90</sup>, also similar to that reported by Rahnama et al. (2003) following a 90 min treadmill protocol. However, Rahnama et al. (2003) observed significant reductions in both concentric knee flexion and extension peak torque during the treadmill protocol which contradicts results from the present investigation. This divergence in findings may be explained by differences in the exercise protocols employed. The free-running SAFT<sup>90</sup> involves forwards, backwards, sideways and cutting actions throughout the course. The activity profile incorporates 1269 transitions in speed (on average once every 4.3 s) and 1350 changes in direction over the full 90 min, reflective of ~1250 activities (Mohr et al. 2003) and 496 deceleration movements observed during actual matches (Bloomfield et al., 2008). In contrast, the motorised treadmill protocol employed by Rahnama et al. (2003) inhibits the ability to incorporate utility movements, due to the inherent unilateral belt movement, or instantaneous acceleration/deceleration. Also, the activity profile contained only 92 discrete bouts of activity during the full 90 min, thus increasing time spent performing individual movement bouts. In particular, high intensity cruising and sprinting comprised over 50% of total distance compared with ~16% during actual matches (Thatcher and Batterham, 2004) and just over 15% during the SAFT<sup>90</sup>. It could be speculated that this extra high-intensity

demand may have created additional muscular requirement to match the load imposed by the utility movements and acceleration/deceleration demands of the SAFT<sup>90</sup>. Consequently, results from the current study may be more representative of the response associated with actual match-play.

In support of findings from the current investigation, Greig (2008) reported no effect of fatigue on either concentric knee flexion or extension peak torque during a 90 min treadmill-based soccer simulation. Also, significant decreases in eccentric knee flexion peak torque of 23.9% (at 300 °s<sup>-1</sup> angular velocity) and in the functional eccH:conQ ratio of 22.9 and 22.6% (at 180 °s<sup>-1</sup> and 300 °s<sup>-1</sup> angular velocity, respectively) were observed between pre- and post-exercise. However, comparisons of these results to current findings should be treated with caution due to the differing isokinetic angular velocities selected by Greig (2008) to that chosen in the current study (120 °s<sup>-1</sup>). Furthermore, in the investigation by Greig (2008) subjects performed one of two randomised isokinetic dynamometry routines comprising five repetitions at three isokinetic speeds for either concentric knee extension and flexion, or eccentric knee extension and flexion at 15 min intervals during the 90 min protocol. The more frequent contractions and thus more demanding isokinetic routine administered by Greig (2008) may have increased the fatigue effect on the muscular strength results observed. However, it is unlikely that the volume of contractions caused additional fatigue in the present study since no significant changes in muscle strength were observed using the same dynamometry routine during a 90 min intermittent treadmill protocol (see pilot results in Chapter 3). Thus, it could be postulated that the utility movements and rapid acceleration/deceleration demands in the SAFT<sup>90</sup> may have more significantly induced impaired muscle strength with fatigue.

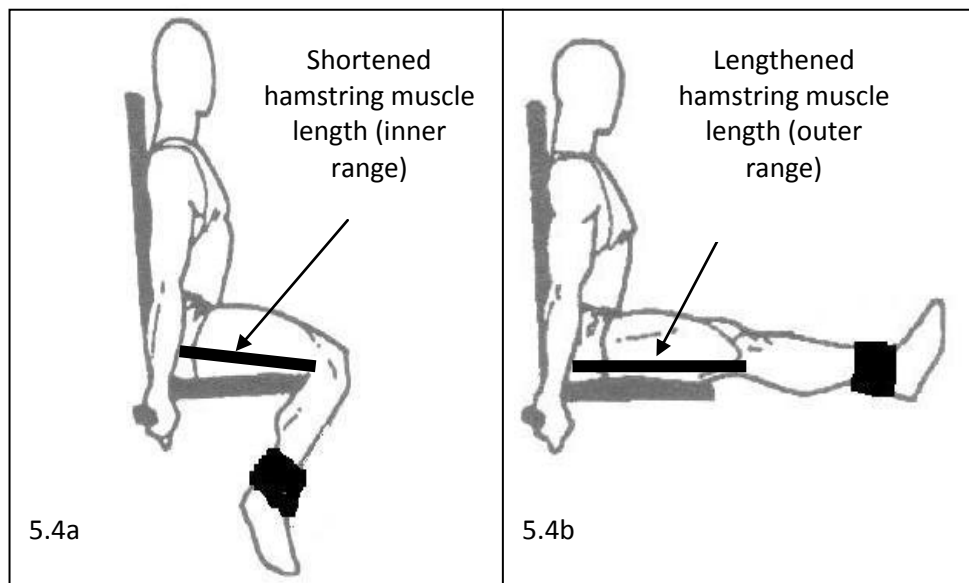


The decline in eccentric hamstring strength with fatigue observed in the present study is commonly associated with hamstring strain injury risk (Rahnama et al., 2003; Woods et al., 2004; Greig, 2008), since muscles are most susceptible to injury during powerful eccentric contractions (Garrett, 1996; Verrall et al. 2001; Brockett et al. 2004). Hamstring injury may be most likely to occur during fatigued sprinting when increased lower limb velocity and reduced hamstring muscle length (indicated in the previous chapter) may cause extra strain on the hamstrings to decelerate the lower limb within a reduced range during the late swing phase. Decreased eccentric hamstring strength resulting in reduced functional eccH:conQ strength ratio with fatigue may indicate insufficient hamstring strength to counteract the force of the quadriceps muscle group to avoid strain injury. The temporal pattern of this strength impairment during the SAFT<sup>90</sup> furthermore appears to corroborate findings from epidemiological research of increased susceptibility to hamstring injury during the late stages of matches (Woods et al., 2004).

Findings from the present investigation may be the first to report changes in knee flexor and extensor angles of peak torque (APT) with fatigue during simulated soccer match-play. The results revealed a shift in concentric knee flexion and extension peak muscle tension in the direction of longer muscle lengths during the SAFT<sup>90</sup>. This supports findings by Brockett et al. (2001) following fatigue induced by an acute bout of eccentric exercise using “hamstring lowers”, as the SAFT<sup>90</sup> had previously been shown to reduce eccentric hamstring strength with fatigue. The shift in concentric knee flexor and extensor APT towards longer muscle lengths may be explained by the “popping sarcomere hypothesis” proposed by Morgan (1990). With fatigue, micro tears occur within a muscle with effective compliance of the muscle fibre increasing, leading to a shift of the whole muscle’s length-tension relationship towards longer lengths (Morgan, 1990).

A shift in the muscle APT towards longer muscle lengths after eccentric contractions may imply a significantly greater loss of relative force at a shorter muscle length compared to optimal or longer lengths (Byrne et al., 2001). Consequently, this may increase susceptibility to muscle damage and therefore risk of injury (Brockett et al., 2001). However, LaStayo et al. (2003) argued that an increase in stiffness and peak torque at longer muscle lengths may actually increase force production before failure therefore helping prevent active muscle strain injuries by improved stability. The disparity surrounding this subject area suggests that further research is warranted.

The change in eccentric hamstring APT was also significantly altered with time during the SAFT<sup>90</sup>. However, contrary to the concentric muscle actions tested, the eccentric hamstring APT revealed a shift towards a shorter muscle length with fatigue. This finding may have important implications for injury risk. Brughelli and Cronin (2007) proposed that peak torque generation at a shorter than optimum muscle length (Figure 5.4a) would result in more of the muscle operating range being on the descending limb of the length-tension curve. Muscles are more likely to become injured when operating in a more lengthened position with peak torque generated at shorter muscle lengths (Garrett, 1990; Brockett et al., 2001; Brockett et al., 2004; Morgan and Proske, 2004; Proske et al., 2004 Figure 5.4b). Therefore, this finding may help explain increased predisposition to hamstring strains during the latter stages of matches, especially with the concurrent deterioration in eccentric hamstring peak torque observed.



**Figure 5.4.** Diagrammatic representation of: 5.4a. Inner range hamstring muscle length. 5.4b. Outer range hamstring muscle length

### 5.5. Conclusions

The SAFT<sup>90</sup> produced a time dependant decrease in eccentric knee flexor strength and consequently in the functional eccH:conQ strength ratio. Additionally, the results are the first to show changes in knee flexor and extensor angles of peak torque during multidirectional, soccer-specific fatigue. There was a shift in the angle of peak torque towards longer muscle lengths during concentric knee flexion and extension actions with time, whereas for the eccentric knee flexion action there was a shift towards a shorter muscle length during the SAFT<sup>90</sup>.

These findings may have implications for increased predisposition to hamstring strain injury during the latter stages of soccer matches. Researchers and club trainers and medical staff should attempt to take into account this fatigue effect associated with soccer match-play when designing hamstring injury prevention programmes. Strategies that can reduce the negative effects of fatigue during match-play may help lower the risk of hamstring

injury at the end of matches. In light of the current findings, such injury prevention strategies should focus on maintaining eccentric hamstring strength during soccer-specific fatigue. This could involve altering the timing of when eccentric hamstring strengthening exercises are employed during training from the traditional approach of non-fatigued to a new strategy of fatigued strength training. Regarding the law of specificity (Kraemer et al., 2002), training in a fatigued state could help improve performance in a fatigued state which may then have beneficial implications for hamstring injury prevention.

**Chapter 6. Fatigued Eccentric Hamstring Strength Training  
Improves Muscle Fatigability during Simulated Soccer Match-  
play.**

## **6.1. Introduction**

Hamstring strains are one of the most common injuries in professional soccer (Arnason et al., 1996, 2004a; Hawkins and Fuller, 1999; Hawkins et al., 2001; Woods et al., 2004) incurring considerable financial costs to clubs. Epidemiological research has reported a doubling in the rate of hamstring injury over time between 1983 and 2004 (Ekstrand and Gillquist, 1983a; Woods et al. in 2004). Despite the high and apparently increasing incidence of hamstring strains in contemporary soccer research into their prevention is limited.

There is widespread agreement that hamstring strain injury is likely to be the result of an interaction between multiple risk factors (Hoskins and Pollard, 2005a). Eccentric hamstring strength is a fundamental aetiological risk factor for hamstring strains (Mann et al., 1986), as eccentric contractions are both an integral part of the functional repertoire of the hamstrings and when muscles are most susceptible to injury (Verrall et al. 2001; Brockett et al. 2004). Furthermore, fatigued muscles produce and absorb less force before reaching the degree of stretch that causes injury (Mair et al., 1996). Thus, the interaction between eccentric hamstring strength and fatigue has been the subject of recent investigation regarding hamstring injury risk.

Research has shown reduced eccentric hamstring strength during the latter stages of simulated soccer match-play (Greig, 2008; Rahnama et al., 2003), and was also demonstrated in the previous chapter (Chapter 5) after completing the free-running, multidirectional SAFT<sup>90</sup>. Epidemiological data has reported a concurrent increase in the incidence of hamstring strains during the latter stages of soccer matches (Woods et al.,

2004). Therefore, increased hamstring injury risk due to reduced eccentric hamstring strength with fatigue experienced during soccer match-play would seem logical.

Research has hypothesised that improving players eccentric hamstring strength may be crucial for injury prevention (Mjøl̄snes et al., 2004). Following a 10-week training intervention period, subjects performing eccentric hamstring strengthening exercises showed an 11% increase in eccentric hamstring peak torque compared to baseline values (Mjøl̄snes et al., 2004). This may increase the hamstring muscles ability to absorb a greater amount of force before reaching the point of failure (Garrett, 1990).

The strategy of eccentric hamstring strengthening exercises has subsequently been used to investigate the prevention of hamstring strains in soccer (Árnason et al., 2008). Findings revealed that an intervention strategy of Nordic hamstring lowers (an eccentric hamstring strengthening exercise) during the warm-up of training sessions significantly reduced ( $P < 0.05$ ) the incidence of hamstring strains during total training and competition compared with baseline data and alternate interventions. However, during matches alone there was no significant difference ( $P > 0.05$ ) in the rate of hamstring strains for the group performing the Nordic hamstring lowers between baseline and intervention period. This may be explained by the timing of the intervention as the resting, non-fatigued strength gains may not have been maintained during the latter stages of matches when players are at greatest risk of injury (Woods et al., 2004).

Previous research (Árnason et al., 2008; Mjøl̄snes et al., 2004) has not investigated changes in strength during simulated soccer match-play following strength training injury prevention programmes conducted in a non-fatigued state. Therefore, it is unknown whether players are able to maintain eccentric hamstring strength when fatigued at the ends

of each half. This may be crucial for injury prevention considering the reduction in eccentric hamstring strength at these times of simulated match-play shown in the previous chapter of this thesis (Chapter 5) and corresponding high incidence of hamstring strain injury during actual matches (Woods et al., 2004). Regarding the law of specificity (Kraemer et al., 2002) it could be hypothesised that performing strengthening exercises in a fatigued state may help improve and/or maintain strength in a fatigued state. Hence, the objective of the study was to compare the effects of performing eccentric hamstring strengthening exercises during either the warm-up or cool down of soccer training sessions on hamstring muscle strength fatigability during simulated soccer match-play.

## **6.2. Methods**

### Participants

Sixteen male, semi-professional soccer players (Mean  $\pm$  SD; Age: 21.3  $\pm$  2.9 yrs; Height 185.0  $\pm$  8.7cm; Body Mass 81.6  $\pm$  6.7kg) took part in the investigation. All players were regular first or second team members of the university soccer teams and completed, on average, two squad training sessions and two matches per week. Subjects were only included in the study if they were not injured or rehabilitating from an injury at the time of testing at baseline and post-intervention, and did not have a history of a previous hamstring injury within three months prior to baseline testing. Ethical approval for the study obtained in accordance with the Departmental and University ethical procedures. Written, informed consent was obtained prior to data collection.

### Experimental Design

At the beginning and end of an eight week intervention period, subjects completed the SAFT<sup>90</sup> (see Chapter 3), divided into two 45 min periods separated by a 15 min passive rest



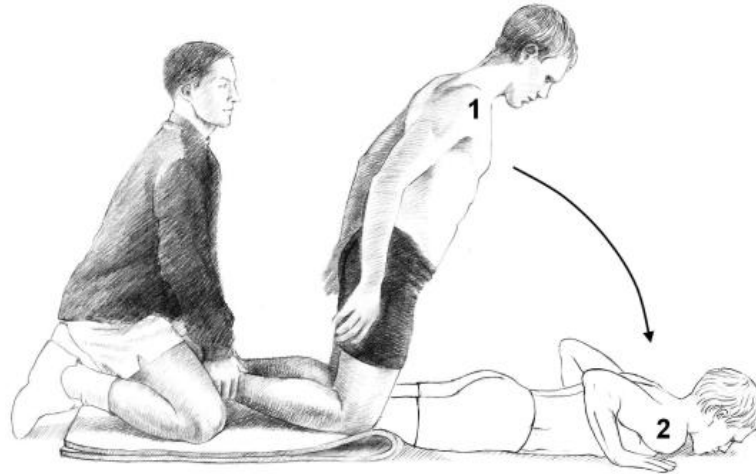
period (half-time). Prior to exercise ( $t_0$ ), at half-time ( $t_{45}$ ) and post-exercise ( $t_{105}$ ), subjects performed three maximal dominant limb isokinetic contractions of concentric (conH) and eccentric knee flexion (eccH) and concentric knee extension (conQ) (for further details of the dynamometry setup and protocol see Chapter 5).

All testing was conducted at the same time of day to account for the effects of circadian variation on variables measured (Reilly and Brooks, 1986). Subjects had performed no vigorous exercise 24h prior to testing, nor consumed any caffeine or alcohol. Baseline and post-intervention testing were conducted during the first three months of the 2007/2008 English competitive soccer season.

### Intervention

After baseline testing subjects were randomly allocated into one of two training groups, either the Warm-up group (WU;  $n = 8$ ) or Cool-down group (CD;  $n = 8$ ). Each group comprised of half first and second team players to account for differences in training between the teams. Both groups incorporated a programme of Nordic hamstring lowers (Mjøl̄snes et al., 2004) into bi-weekly soccer training sessions over the 8-week intervention period. The CD group performed the Nordic hamstring lowers during the cool-down of training sessions (ie. in an exercised state), whereas the WU group performed the exercises during the warm-up (ie. in a resting state). The training protocol and load for the Nordic hamstring lowers involved gradually increasing sets and repetitions of the exercise over the first four weeks of the intervention period and maintaining the training load over the following four weeks (Mjøl̄snes et al., 2004). Nordic hamstring lowers is a partner exercise whereby the subject attempts to resist a forward-falling motion of their upper body, whilst stabilised with their lower legs and ankles secured to the ground by their partner, thereby

maximising the eccentric load imposed on the hamstrings. The exercise programme has been shown to increase eccentric hamstring strength and be a safe exercise in this player population resulting in no injuries over a 10-week period (Mjølsnes et al., 2004).



**Figure 6.1.** The Nordic hamstring lowers exercise. Reproduced from Bahr and Mæhlum (2002)

During the 8-week intervention match and training exposure along with compliance rate with the prescribed exercise programme were logged by the players on a specialised form. Following the intervention period, subjects were invited back for re-testing using identical methods previously employed.

### Data Analysis

The dependent variables selected from the isokinetic strength indices were gravity-corrected peak torque (PT), with mean peak torque values calculated from the three attempts following standard procedures (Rahnama et al., 2003). The variables included: concentric quadriceps (conQ) and hamstring (conH) peak torque (PT) and eccentric hamstring (eccH) PT which enabled the calculation of the traditional concentric

hamstrings:concentric quadriceps (conH:conQ) and the functional eccentric hamstrings:concentric quadriceps (eccH:conQ) strength ratio's.

Before using parametric tests, the assumption of normality was verified using the Kolmogorov–Smirnov test. A two-way (time by group) mixed-factorial ANOVA was used to assess differences in strength variables measured between groups at each of the three time points:  $t_0$ ,  $t_{45}$  and  $t_{105}$ . Effect sizes were determined for clinical significance using the Cohen (1988) method which defines 0.02, 0.15 and 0.35 as small, medium and large effect sizes respectively, with 95% confidence intervals (CI). Statistical analysis was processed using SPSS statistical software (version 14.0 Chicago, IL<sup>®</sup>) with significance levels set at  $P \leq 0.05$ .

### **6.3. Results**

During the 8-week intervention period the WU and CD groups had a compliance rate with the intervention programme of 91.2% and 89.7%, respectively. There were no significant differences in the compliance rate or total amount of soccer training and match-play between groups during the intervention period ( $P > 0.05$ ).

In all statistical tests conducted to analyse differences between group results the Levene  $F$  Statistic of equality for error variances was non-significant ( $P > 0.05$ ), therefore indicating acceptable equality between groups at baseline.

There was a significant main effect of group for conH PT ( $P < 0.05$ ; Partial Eta squared = 0.28). There was also a significant interaction effect of time by group for conH PT ( $P < 0.05$ ; Partial Eta squared = 0.30). The CD group had a significant increase in conH PT at  $t_{45}$  (Difference [D] -CD  $t_{45}$ :  $24.0 \pm 24.0$  vs D-WU  $t_{45}$ :  $-4.9 \pm 21.0$  %;  $P < 0.05$ , Cohen's  $d =$

1.03; 95% CI 0.17-1.90) and  $t_{105}$  (D-CD  $t_{105}$ :  $17.3 \pm 13.7$  vs D-WU  $t_{105}$ :  $2.1 \pm 11.1$  %;  $P < 0.05$ , Cohen's  $d = 0.26$ ; 95% CI  $-0.43-0.94$ ).

There was a significant main effect of group for eccH PT ( $P < 0.05$ ; Partial Eta squared = 0.28). There was also a significant interaction effect for eccH PT ( $P < 0.05$ ; Partial Eta squared = 0.65). The WU group displayed a significant increase in eccH PT compared with the CD group at  $t_0$  (D- CD  $t_0$ :  $-7.9 \pm 24.7$  vs D-WU  $t_0$ :  $17.4 \pm 9.7$  %;  $P < 0.05$ , Cohen's  $d = 0.57$ ; 95% CI 0.09-1.04). Conversely, the CD group displayed significant increases in eccH PT at  $t_{45}$  (D- CD  $t_{45}$ :  $31.5 \pm 25.7$  vs D-WU  $t_{45}$ :  $-4.9 \pm 25.0$  %;  $P < 0.05$ , Cohen's  $d = 0.81$ ; 95% CI 0.21-1.42) and  $t_{105}$  (D- CD  $t_{105}$ :  $40.7 \pm 24.4$  vs D-WU  $t_{105}$ :  $-6.4 \pm 23.2$  %;  $P < 0.01$ , Cohen's  $d = 1.01$ ; 95% CI 0.47-1.55; Figure 6.2).

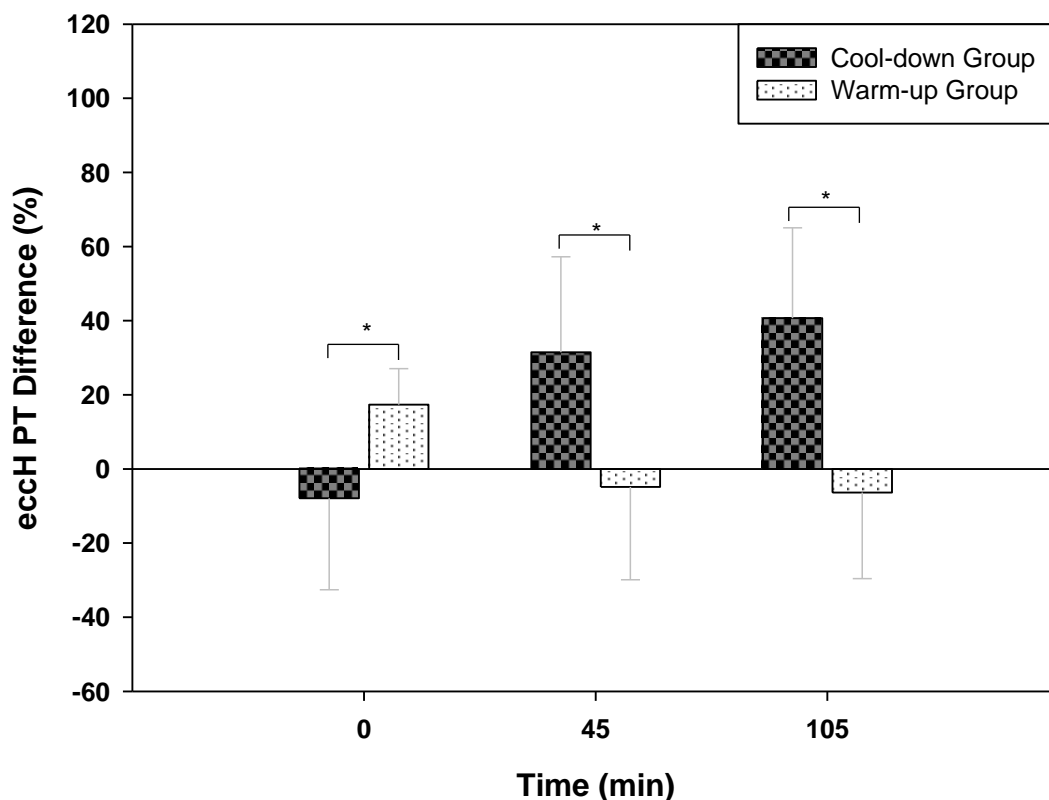
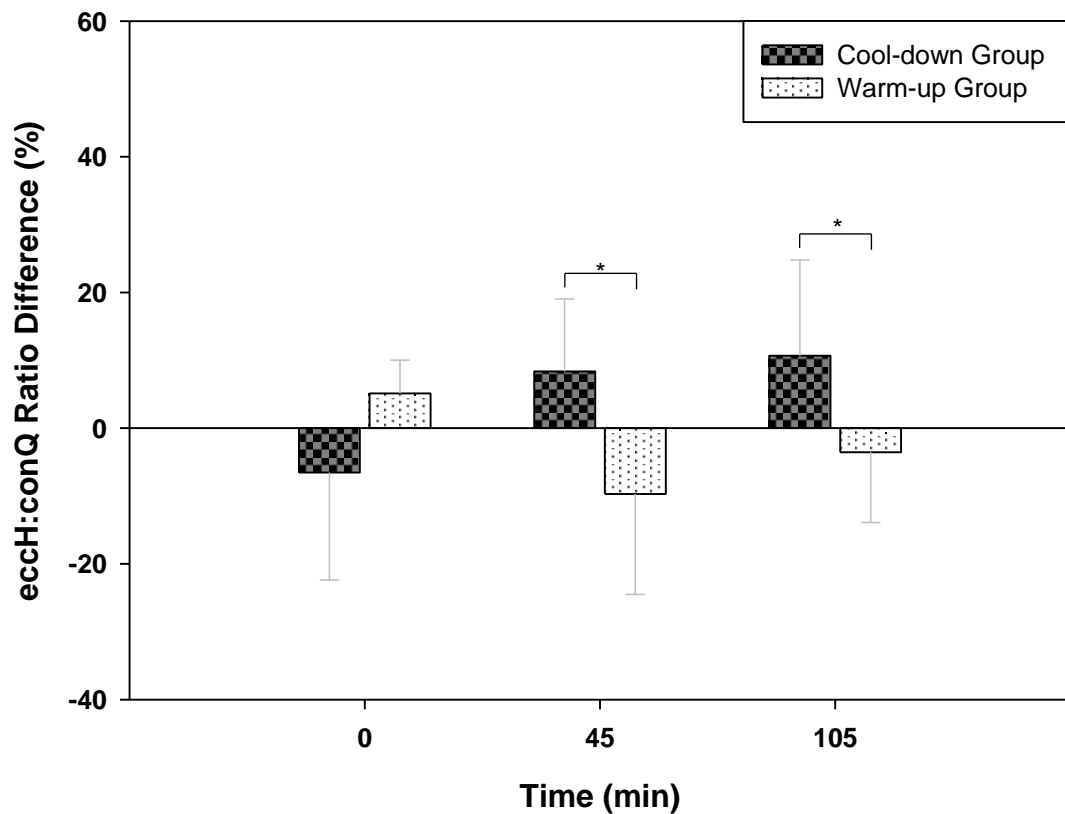


Figure 6.2. Changes in eccentric hamstring peak torque between pre-and post-intervention for cool-down and warm-up groups

\*Significant difference between Groups ( $P < 0.05$ )

Subsequently, there was a significant interaction effect in the functional eccH:conQ ratio ( $P > 0.05$ ; Partial Eta squared = 0.15). The CD group had a significant increase in the eccH:conQ ratio (Figure 6.3) compared with the WU group at  $t_{45}$  (D- CD  $t_{45}$ :  $8.4 \pm 10.7$  vs D-WU  $t_{45}$ :  $-9.7 \pm 14.8$  %;  $P < 0.05$ , Cohen's  $d = 1.02$ ; 95% CI 0.24-1.81) and  $t_{105}$  (D- CD  $t_{105}$ :  $10.7 \pm 14.1$  vs D-WU  $t_{105}$ :  $-3.5 \pm 10.4$  %;  $P < 0.05$ , Cohen's  $d = 0.70$ ; 95% CI 0.04-1.36).



**Figure 6.3.** Changes in functional eccentric hamstring:concentric quadriceps ratio between pre-and post-intervention for cool-down and warm-up groups

\*Significant difference between Groups ( $P < 0.05$ )

#### 6.4. Discussion

This is the first study to investigate the effect of timing of eccentric hamstring strengthening exercises during soccer training. Findings indicate that the timing of the

strengthening exercises during training sessions affects the temporal pattern of strength gains during simulated soccer match-play. Following the intervention period, players performing Nordic hamstring lowers during the warm-up of training had significantly increased resting eccentric hamstring muscle strength and subsequently functional eccH:conQ strength imbalance. Conversely, players performing the exercise during the cool-down demonstrated better maintained eccentric hamstring strength and preserved functional eccH:conQ strength imbalance throughout simulated soccer match-play.

The initial gain in pre-exercise eccentric hamstring peak torque and consequently eccH:conQ strength ratio post-intervention by the warm-up group supports previous research by Mjølsnes et al. (2004). In their investigation, the authors compared eccentric versus concentric hamstring strength training in well-trained soccer players. The results revealed that Nordic hamstring lowers were more effective than concentric hamstring curls at developing eccentric hamstring strength and improving the eccH:conQ strength ratio. Findings showed an 11% increase in eccentric hamstring peak torque and the eccH:conQ strength ratio post-intervention, whereas current findings revealed increases of 6.8% and 4.7%, respectively. The divergence in results may be explained by different isokinetic test speeds administered by Mjølsnes et al. (2004) to that of the present investigation ( $60^{\circ}\text{s}^{-1}$  and  $120^{\circ}\text{s}^{-1}$ , respectively). However, as higher test speeds correlate with the high velocity involved in functional movements that may better replicate injury mechanisms (Dowson et al., 1998) current findings could be considered more valid in relation to hamstring injury risk.

The increase in resting eccentric hamstring strength observed by the warm-up group may imply reduced risk of hamstring strain injury as injury risk is considered greatest with muscle weakness during eccentric contractions (Mair et al., 1996). However, this initial

strength gain was not maintained post-intervention at either half-time or post-exercise during the SAFT<sup>90</sup>. Given that epidemiological research has observed players to be at greatest susceptibility of hamstring injury at this time (Woods et al., 2004), the potential reduction in injury risk for the warm-up group when fatigued during soccer match-play may be doubtful. This theory may concur with work by Árnason et al. (2008) who investigated the efficacy of performing Nordic hamstring lowers in a non-fatigued state in the prevention of hamstring strains in elite soccer (Árnason et al., 2008). Findings revealed no significant difference in hamstring injury rate for teams performing the Nordic hamstring lowers exercise between baseline and intervention period during soccer matches. However, the authors did not speculate on the mechanism of this unanticipated finding.

Along with implementing the traditional approach of strength training in a non-fatigued state, the present study also adopted an innovative strategy of fatigued strength training for injury prevention. Post-intervention results for the cool-down group showed better maintained eccentric hamstring strength and preserved eccH:conQ muscular balance at half-time and post-SAFT<sup>90</sup> compared to baseline values and post-intervention results for the warm-up group. Therefore, the fatigued training strategy was shown to reduce the negative effects of fatigue on markers of hamstring injury risk at the ends of each half of simulated soccer match-play. This may suggest reduced risk of incurring hamstring strains at the times of highest susceptibility to injury during matches (Woods et al., 2004). However, without match-play injury incidence data concurrently recorded during the intervention period this cannot be confirmed. Nevertheless, this theory may corroborate with work by Verrall et al. (2005) who reported a significant reduction ( $P < 0.05$ ) in match-play hamstring injury incidence rate in Australian Rules Football players after an intervention strategy incorporating a football specific drill to improve eccentric hamstring strength

performed in a fatigued state. However, as the intervention strategy was multi-faceted, including flexibility and aerobic interval training, it is difficult to determine whether the reduced injury rate was the result of an individual aspect of the strategy or an interaction of all components.

In the present investigation, findings from the cool-down group not only showed better maintained eccentric hamstring strength during the SAFT<sup>90</sup> post-intervention but also better maintained concentric hamstring strength. This may be explained by the mechanics and muscle actions involved in performing Nordic hamstring lowers. During the exercise, once players have controlled the forward motion of their body to the ground they must recover to the starting position (that is vertical) to complete the subsequent repetition. To facilitate this action, players forcefully push with their hands on the ground and at the same time exert some concentric contraction of the hamstrings (Mjølunes et al., 2004). Thus, the same mechanisms responsible for improving eccentric hamstring fatigability by training in a fatigued state may similarly apply to improving concentric hamstring fatigability. This enhanced preservation of concentric hamstring strength post-intervention could aid performance by maintaining players' ability to run, sprint, jump and tackle vigorously under fatigued conditions during soccer matches (Rahnama et al., 2003).

The present findings of better maintained strength following the fatigued training strategy are believed to be unique within research concerning soccer-specific fatigue and hamstring injury risk. However, they may be explained by theories regarding muscle physiology and adaptation. In regard to the law of specificity (Kraemer et al., 2002) in strength training, the nature of the training load produces specific responses and adaptations. Therefore, conceivably training in a fatigued state may improve subsequent performance in a fatigued state. This response could be related to post-activation potentiation involved in complex



training. Complex training involves carrying out heavy resistance exercises typically prior to performing an explosive movement with similar biomechanical characteristics referred to as a complex pair (Hodgson et al., 2005). When repeated for multiple sets, over time this could produce long-term changes in the ability of the muscle to generate power (Hodgson et al., 2005). If the exercises are therefore performed in a fatigued state, this may be hypothesised to enhance long-term ability to generate greater muscle power in a fatigued state. This could be the result of a new motor learning component to create training-induced neuromuscular adaptations of alternate muscle recruitment strategies according to the specific mode of exercise training. Alternatively, theories regarding principals of myoplasticity, increased mitochondrial mass, increased free fatty acid utilisation, and increased capillary density have been proposed as positive adaptations following fatigued resistance training (Brooks et al., 2005). However, as little research has investigated these hypotheses, additional study is warranted to examine muscular adaptations following fatigued strength training. This could provide vital knowledge for better understanding fundamental concepts to consider when designing future injury prevention programmes.

## **6.5. Conclusions**

Findings from the present study indicated that performing eccentric hamstring strengthening exercises during the cool-down rather than warm-up of soccer training sessions more effectively maintained eccentric hamstring strength and preserved the functional eccH:conQ strength ratio throughout simulated soccer match-play. These findings may have implications for future injury prevention programmes to reduce hamstring strain injury risk, particularly during the late stages of matches. Based on the evidence provided, soccer club trainers and medical staff should prescribe eccentric hamstring strengthening exercises at the end of training sessions for injury prevention.

## **Chapter 7. General Discussion and Conclusions**

## **7.1. General Discussion**

The aim of this thesis was to investigate the mechanisms of hamstring strains in soccer considering the influence of fatigue associated with match-play and develop a strategy for injury prevention. The purpose of this final chapter was to integrate findings from the experimental studies in the thesis to form an overall conclusion of the research conducted as well as discussing potential limitations and directions for future work.

The literature into injuries in soccer has reported hamstring strains as the most common injury to high-level players, accounting for 12-16% of all injuries (McGregor and Rae, 1995; Hawkins et al., 2001; Woods et al., 2004; Sheppard and Hodson, 2006). On average, the injury results in 21 days of training and three competitive matches missed (Woods et al., 2004). Hamstring strains are primarily sustained through non-contact situations, with sprinting the primary injury mechanism (Latella et al., 1992; Hawkins and Fuller, 1999; Hawkins et al., 2001; Arnason et al. 2004; Woods et al., 2004; Sheppard and Hodson, 2006).

Of the various aetiological risk factors for hamstring strains, fatigue may be a crucial predisposing factor for increased injury risk. Epidemiological research has reported an increased incidence rate of hamstring strains during the latter stages of each half of soccer matches (Woods et al., 2004). Fatigue may be hypothesised to contribute to injury by impairing muscle flexibility, strength or movement mechanics. However, previous research investigating injury risk factors affected by fatigue has not considered the multidirectional nature of soccer match-play. Utility movements contribute up to 36.9% of total distance covered during matches (Thatcher and Batterham, 2004) and have been reported to greatly increase the physiological load (Kirkendall, 2000). This, combined with the high proportion

of acceleration/deceleration movements performed (Bloomfield et al., 2008), has been postulated to increase the eccentric stresses placed on hamstrings to increase their chance of failure (Woods et al., 2004).

In order to replicate the fatigue associated with soccer matches, in Chapter 3 a new soccer simulation based on the demands of modern match-play was developed. In light of pilot testing, a free-running 90 min version of the recently developed Soccer-specific Aerobic Field Test (SAFT<sup>90</sup>) was created. The primary difference of the SAFT<sup>90</sup> to alternate soccer simulations was the incorporation of utility movements involving forwards, backwards and sideways running and cutting actions as well as acceleration/deceleration demands. The SAFT<sup>90</sup> was developed from contemporary time motion analysis data obtained from 2007 English Championship Level matches (Prozone<sup>®</sup>). In total, the exercise protocol lasted 90.43 min and subjects covered a distance of 10.78 km through a variety of frequently changing movement intensities observed during soccer (standing, walking, jogging, striding and sprinting). Thus, the SAFT<sup>90</sup> was deemed to accurately reflect the activity profile of modern soccer.

The SAFT<sup>90</sup> was assessed by measuring subjects' physiological responses and sprint performance throughout the simulation, with the results compared to actual match-play observations as well as alternate soccer simulations. The physiological responses to the SAFT<sup>90</sup> revealed a mean heart rate of 162 b·min<sup>-1</sup> (82.9% HR<sub>max</sub>) which was consistent with previous match-play observations using high-level English players (156 b·min<sup>-1</sup>; 82% HR<sub>max</sub>; Edwards and Clark, 2006). Additionally, oxygen consumption during the SAFT<sup>90</sup> corresponded to 69.1% of VO<sub>2max</sub> as was comparable with mean values of 70% VO<sub>2max</sub> attributed to match-play (Mohr et al., 2004). Along with physiological responses, sprinting performance was reduced as a function of time during the SAFT<sup>90</sup> to be 95.9% and 92.3%

of maximal speed at the ends of the first and second halves, respectively. This concurred with previous research reporting a 9% reduction in sprint performance between the first and last 15 min period of competitive games (Bangsbo and Mohr, 2005). The impaired sprint performance observed at the ends of each half of the match simulation may relate to increased susceptibility to hamstring injury (frequently sustained whilst sprinting) at this time during matches (Woods et al., 2004). Therefore, it was hypothesised that sprinting technique or muscle functioning may be negatively affected by fatigue to increase risk of injury. In consideration of this hypothesis, the second and third experimental chapters employed the newly developed SAFT<sup>90</sup> to investigate temporal changes in sprinting technique and muscular strength during simulated soccer match-play.

In Chapter 4, sprinting kinematics relating to factors associated with hamstring injury risk were examined using the SAFT<sup>90</sup>. The results substantiated findings from Chapter 3 revealing impaired sprint performance during the latter stages of each half of the match simulation. Findings also showed a time dependant alteration in kinematics of sprinting technique during the SAFT<sup>90</sup>. This was demonstrated during fatigued sprinting as reduced flexibility of the hamstring muscle group indicated during the late swing phase of the sprint cycle. A concurrent increase in anterior pelvic tilt and shank segmental velocity, potentially a result of greater elastic recoil from increased rectus femoris length indicated earlier in the stride cycle, was observed with fatigue. This may cause additional strain on the hamstring musculo-tendinous unit. Consequently, findings suggested increased risk of hamstring strain injury whilst sprinting with fatigue associated with the late stages of soccer matches, thus supporting the temporal pattern of injury during matches (Woods et al., 2004).

Impaired sprinting performance and altered technique to increase risk of hamstring injury was primarily observed at the ends of each half of the SAFT<sup>90</sup>, however a similar

observation of impaired sprinting ability was indicated immediately following the half-time interval. Interestingly, at 60 min during the soccer simulation players showed an improvement in sprinting performance and a recovery towards non-fatigued sprinting technique. This could be due to the 15 min period of inactivity during half-time causing reduced muscle temperature and flexibility which subsequently increased with exercise during the start of the second half (Mohr et al., 2004). Consequently, this may suggest increased risk of hamstring injury at the beginning of the second half of matches. In support of this theory, epidemiological research has documented an increased number of injuries immediately following half-time (Rahnama et al., 2002).

Regarding limitations, the study failed to concurrently examine muscle activation for agonist and antagonist muscle groups during sprinting using electromyography (EMG) which may have provided further information regarding muscle functioning and injury susceptibility. Although this method was initially attempted, limitations with technical equipment caused failed data collection beyond 30 min during the testing session which lasted approximately 120 min. Thus, with enhanced technology this may be suggested for future investigation into functional examination of muscular requirements during sporting movements. However, the failure to record EMG was not deemed to be a significant limitation since in Chapter 5 muscle strength profiling of the knee flexors and extensors during the SAFT<sup>90</sup> was investigated using isokinetic dynamometry. Although this equipment may have reduced external validity when extrapolating information to a sporting context, it does provide a useful tool for studying dynamic muscle function after exercise (Baltzopoulos and Gleeson, 2001). Furthermore, the equipment also allows angle of peak torque (APT) to be recorded which has been suggested to have important implications for injury risk (Brockett et al., 2001).

The results from Chapter 5 showed a time dependant decrease in eccentric knee flexor strength and consequently in the functional eccH:conQ strength ratio during the SAFT<sup>90</sup>. These factors have been implicated with increased risk of hamstring injury and specifically when fatigued (Mair et al., 1996). Furthermore, the temporal pattern of these strength decrements during the SAFT<sup>90</sup> corresponded to the pattern of increased risk of hamstring injury when fatigued during soccer matches (Woods et al., 2004). The study also revealed innovative findings regarding changes in knee flexor and extensor APT during simulated match-play. A shift in the APT towards longer muscle lengths for concentric knee flexor and extensor muscle actions was observed at the ends of each half of the SAFT<sup>90</sup>. Conversely, at these time points there was a shift in the APT towards a shorter muscle length for the eccentric knee flexor muscle action. As muscles are considered more susceptible to injury when operating in a more lengthened position (Garrett, 1990), these findings may support the supposition that muscles are at increased risk of injury with fatigue during eccentric contractions (Mann et al., 1986; Mair et al., 1996).

The findings of reduced eccentric hamstring strength with soccer-specific fatigue in Chapter 5 may have further implications for hamstring injury risk in consideration of results from the previous experimental chapter investigating changes in sprinting kinematics. An increase in shank segmental velocity during sprinting was observed at the ends of each half of the SAFT<sup>90</sup>. This movement must be counteracted by the eccentrically contracting hamstrings. However, reduced eccentric hamstring peak torque at the end of each half of the SAFT<sup>90</sup> as observed in Chapter 5 may indicate impaired ability of the hamstrings to decelerate this action and avoid injury. Furthermore, the shift in eccentric hamstring APT towards shorter muscle lengths when fatigued may also suggest an impaired capability of the hamstrings to decelerate the end point of the forward extending

shank at the late swing phase of sprinting. Research has hypothesised that hamstring strain injury is most likely to be incurred at this point (Agre, 1985; Mair et al., 1996) which the current results would appear to support.

The final aim of this thesis was to use the information ascertained from the previous investigations into mechanisms of hamstring injury during simulated soccer match-play to develop a new strategy of injury prevention. From the findings of Chapters 4 and 5, it was deemed that such a strategy would need to reduce the negative effects of fatigue associated with soccer match-play on hamstring muscle strength. Consequently, considering the law of specificity (Kraemer et al., 2002), a strategy of performing eccentric hamstring strengthening exercises in a fatigued state during soccer training was investigated. The efficacy of this intervention was assessed alongside an identical strength training programme conducted in a non-fatigued state. The programme was performed by two groups bi-weekly over an 8-week period, with isokinetic dynamometry strength testing conducted throughout the SAFT<sup>90</sup> pre- and post-intervention.

The fatigued strength training strategy was shown to be more effective at maintaining eccentric hamstring strength and preserving the functional eccH:conQ strength ratio throughout simulated soccer match-play than the traditional approach of training in a non-fatigued state. This enhanced muscle fatigability may have been achieved through post-activation potentiation involved in complex training. It has been postulated that over time fatigued training could produce long-term changes in the ability of the muscle to generate power (Hodgson et al., 2005). This may have preserved eccentric hamstring strength and subsequently the functional eccH:conQ ratio by creating new motor learning programmes to produce specific neuromuscular responses. Consequently, this better maintained hamstring muscle strength and muscular imbalance could reduce hamstring strain injury



risk during the latter stages of matches when players are at the greatest susceptibility to injury (Woods et al., 2004).

These highly innovative findings within research into soccer-specific fatigue and hamstring injury risk may have important implications for future injury prevention and give rise to a new strategy of training in a fatigued state. However, the findings should be considered in light of there being no control group during the intervention period which was due to a relatively low subject number. Given the potential importance of the findings, larger scale investigation is warranted and future researchers should consider incorporating a control group along with the two intervention groups. This will improve the experimental design and thus create more reliable evidence-based research with which to better inform future practice.

## **7.2. Future Research Recommendations**

The SAFT<sup>90</sup> developed in this thesis was shown to replicate the physiological responses and demands of modern soccer match-play. However, it cannot be proven as a valid match simulation until the same subject population is examined for physiological and performance measures against alternate exercise protocols or actual match-play as may be a direction for future research. Subsequently, considering the vast interest and financial investment in soccer and consequential research attention, alternate versions of the SAFT<sup>90</sup> could be developed for other populations. In particular, exercise protocols could be developed for elite female and high-level youth/academy players using emerging time motion analysis data of match-play. These protocols could be employed as economical lab-based simulations to induce soccer-specific fatigue for future applied research investigations

considering the temporal pattern of injuries during matches for elite female (Tscholl et al., 2007) and youth players (Price et al., 2004).

Work from this thesis investigated the effect of soccer-specific fatigue on kinematics of sprinting (the primary mechanism for hamstring injury; Woods et al., 2004) related to hamstring injury risk considering the temporal pattern of injury during matches (Woods et al., 2004). Epidemiological research has reported additional common soccer injuries such as knee and ankle ligament sprains to demonstrate a similar temporal pattern of match-play injury incidence (Hawkins et al., 2001). These injuries are also frequently sustained through non-contact mechanisms such as cutting, kicking and landing (Hawkins et al., 2001). Thus, future investigation should examine the effect of multidirectional soccer-specific fatigue on alternate non-contact injury mechanisms. This may provide a more detailed knowledge base of injury mechanisms in soccer with which to develop additional injury prevention strategies.

The findings from this thesis principally indicated increased risk of injury with fatigue during the latter stages of simulated soccer match-play. However, results from Chapter 4 also suggested a high risk of injury whilst sprinting during the early stages of the second half following a half-time period of inactivity, corroborating epidemiological observations (Rahnama et al., 2002). Hence, it would be prudent to further investigate half-time re-warm-up strategies for injury prevention. At present, minimal research has been conducted within this area with studies focusing on improving early second half performance (Mohr et al., 2004; Lovell et al., 2007). Strategies that can maintain muscle temperature, flexibility, strength parameters and proprioception during the half-time period should all be considered for future re-warm-up interventions.

The innovative injury prevention strategy of fatigued strength training investigated in the final experimental chapter of this thesis was shown to better maintain eccentric hamstring strength during simulated soccer match-play, thus theoretically reducing hamstring injury risk. Knee and ankle ligament sprains are also associated with increased risk of injury when fatigued (Hawkins et al., 2001). Proprioception exercises are commonly used for the prevention of these injuries (Söderman et al., 2000). Therefore, conceivably the strategy of fatigued training could also be applied to proprioceptive exercises for the prevention of knee and ankle ligament injuries by enhancing proprioceptive fatigability. However, it is also important to gain greater knowledge of the resultant physiological mechanisms and adaptations following a fatigued training programme. This is a poorly researched area that may hold important implications for understanding mechanisms for injury prevention. The information gained could then form the basis to further develop injury prevention strategies.

### **7.3. Conclusions**

Hamstring strains are currently the most common injury in soccer, with fatigue an important injury risk factor (Woods et al., 2004). A new 90 min soccer simulation (SAFT<sup>90</sup>) was developed to reflect the physiological demands and work rate of modern match-play. Sprinting performance was shown to be impaired towards the ends of each half of the SAFT<sup>90</sup>, along with altered technique observed as reduced flexibility of the hamstrings in conjunction with increased shank segmental velocity. A similar time dependant impairment was observed in eccentric hamstring peak torque and functional eccH:conQ strength ratio. Furthermore, there was a concurrent shift in the angle of peak torque for the eccentric hamstring muscle action towards a shorter muscle length. These findings suggested

increased risk of hamstring injury during the latter stages of soccer match-play, corroborating epidemiological data (Woods et al., 2004).

A new strategy for hamstring injury prevention involving fatigued training of eccentric hamstring strengthening exercises was subsequently developed. Following an 8-week intervention, players displayed better maintained eccentric hamstring strength and preserved functional eccH:conQ strength ratio during the SAFT<sup>90</sup> compared with pre-intervention values and also players performing the exercise programme in a non-fatigued state. These findings may have important implications for reducing hamstring injury risk during soccer matches and could give rise to a new strategy of fatigued training for injury prevention. If proven to be successful, this innovative strategy could be applied to multiple injury prevention exercises to help further lower the risk of sporting injury when fatigued.

## **Chapter 8. References**

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