Electromyographic Analysis of the Hamstrings during the ‘Nordic’ Hamstring Exercise

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ABSTRACT

Training using the Nordic Hamstring Exercise (NHE) has been shown to improve factors that may help prevent hamstrings injury, despite this no research group has examined the recruitment characteristics of the hamstrings muscles during this exercise and considered the specificity of training adaptations. The aim of the present investigation was to study the electromyographic (EMG) activity of the hamstrings muscles during the NHE and then to investigate the effect of a 4 week NHE training programme on isokinetic eccentric hamstring peak torque production in both limbs at velocities 60, 120 and 240°/s. Eighteen male professional soccer players (mean ± SD; age, 22.8 ± 3.5 yrs) were randomly assigned to a training or control group. A paired sample *t*-test indicated no difference in the normalised RMS amplitude of the hamstrings between the dominant (DOM) and non dominant (NDOM) limbs ($t_{37} = 0.137$; $P = 0.413$) during the NHE. Two-way repeated measures ANOVA demonstrated no interaction between the medial (MED) and lateral (LAT) muscle regions and the knee position (phase 1, 1st 1/3 of the movement; phase 2, 2nd 1/3 of the movement; phase 3, 3rd 1/3 of the movement) for the RMS EMG amplitude of the hamstrings in the DOM limb ($F_{2,35} = 1.775$, $P = 0.184$). Although no main effect for muscle region was observed ($F_{1,36} = 1.605$, $P = 0.213$), main effects for knee position during the movement on RMS EMG amplitude were demonstrated ($F_{2,35} = 154.354$, $P < 0.001$). Bonferroni corrected post-hoc *t*-tests indicated that the normalised RMS EMG amplitude was significantly higher at phase 2 (11.1±3.8%) and phase 3 (8.6±3.0%) of the movement when compared to phase 1 (3.7±1.8%) of the movement. For the training study, a two-way (2 x 2) between (group) within (time) ANOVA demonstrated an interaction effect for time by group of the DOM and NDOM limbs in isokinetic hamstring peak torque production across assessment velocities (60°/s, DOM $F_{1,16} = 5.11$, $P = 0.04$; NDOM $F_{1,16} = 6.84$, $P = 0.02$; 120°/s, DOM $F_{1,16} = 4.46$, $P = 0.05$; 240°/s DOM, $F_{1,16} = 8.10$, $P = 0.01$; 240°/s, NDOM, $F_{1,16} = 5.68$, $P = 0.03$). Main effects for time for the DOM limb were observed for the slowest velocity (60°/s, DOM, $F_{1,16} = 5.58$, $P = 0.03$), but not for the faster velocities (120°/s, DOM, $F_{1,16} = 2.73$ $P = 0.12$; 240°/s, DOM, $F_{1,16} = 1.24$, $P = 0.28$). Main effects for time for the NDOM limb were observed across all velocities (60°/s, NDOM, $F_{1,16} = 10.96$, $P < 0.001$; 120°/s, NDOM, $F_{1,16} = 6.75$, $P = 0.02$; 240°/s, NDOM, $F_{1,16} = 12.24$, $P < 0.001$). A two-way (2 x 2) repeated measures ANOVA indicated no interaction effects for time by limb across velocities in the training group (60°/s, $F_{1,18} = 0.20$, $P = 0.66$; 120°/s, $F_{1,18} = 0.026$ $P = 0.88$; 240°/s, $F_{1,18} = 2.48$, $P = 0.13$). Main effects for time across all velocities were observed ($F_{1,18} = 23.65$, $P < 0.001$) although no main effects for limb across all velocities were observed ($F_{1,18} = 0.75$, $P = 0.40$). EMG data demonstrates that the hamstrings muscles in both limbs are recruited to a similar extent and the activity levels of the LAT and MED hamstrings were similar during the NHE; with the highest activation levels being observed in the more extended knee joint positions. Isokinetic peak torque data demonstrates that 4 weeks NHE training significantly increases eccentric peak torque production in the hamstrings of both the DOM and NDOM limbs. These results have implications for injury prevention and rehabilitation as increasing eccentric hamstring strength has been identified to reduce hamstrings injuries.

AUTHOR'S DECLERATION

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

Signed ....

Date ...4th March 2........................

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CHAPTER I

INTRODUCTION

Soccer (association football) is without doubt the most popular sport in the world with over 200 million participants world-wide (Patel *et al.*, 2002). As in any physical activity, as participation levels increase, so too does the number of individuals at risk of injury (Leininger *et al.,* 2007). Epidemiological evidence indicates that the injury risk associated with the professional game is significantly higher than other work-based activities (Hawkins and Fuller, 1999). Indeed, it has been calculated that the overall level of injury sustained by professional players is approximately 1000 times higher than for industrial occupations generally regarded as high risk (Hawkins and Fuller, 1999). In the professional game (senior players) the impact of injury to a club has been measured by the number of competitive matches missed (Parry *et al.,* 2006). Absenteeism due to injury may impact a team's performance; specifically, the loss of important first team players from the team may ultimately affect the overall success of a team, leading to reduced income due to a fall in match attendances, and diminishing prize money as a result of low league position, and early cup competition exits (Hawkins and Fuller, 1999; Woods *et al.,* 2002). At youth level, the issue of injury may be considered in relation to the time available to train and perfect technical and tactical skills necessary for success at the highest level of the game (Price *et al.,* 2004). Data obtained from the 38 English academy clubs over two competitive seasons reported that at the junior level of soccer, the average number of days missed due to an injury was 21.9, with an average of 2.31 games missed per injury (Price *et al.,* 2004). One group of researchers has estimated that to become an elite performer, a player must train for over three hours per day for 10 years (Ericsson *et al.*, 1994). When the importance of training is considered, it is clear that the occurrence of injury may compromise the development of young football players. Therefore, to maximise a team's chances of success and to optimise a player's chance of realising their inherent potential, efforts must be made to prevent and control the occurrence of injury (Woods *et al.,* 2002; Price *et al.,* 2004).

A wealth of epidemiological studies have indicated that the majority of injuries sustained by soccer players occur in the lower extremity, with the thigh the major site for injury (Hawkins and Fuller, 1999; Woods *et al.,* 2002; Price *et al.,* 2004; Woods *et al.,* 2004). The high proportion of injuries at the thigh may be attributed to the high incidence of muscle strain injuries, particularly to the hamstrings muscle group. Evidence suggests that a high proportion of hamstrings strain injuries occur during running or sprinting (Price *et al.*, 2003; Woods *et al.,* 2004). During these activities, the injury is usually sustained late in the forward swing phase of the running action at the more extended knee angles as the hamstring muscle group works eccentrically (i.e., lengthens whist generating tension) to prevent hyperextension of the knee and flexion of the hip (Garrett, 1996).

Despite extensive study in the area the precise cause of hamstrings strain injuries still remains unclear (Croisier, 2004). A variety of factors have been implicated in the aetiology of hamstring strain injuries, including muscle weakness (Orchard *et al.*, 1997) and muscle imbalances (Croisier, 2004). In particular, weakness in the eccentric strength of the hamstrings has been suggested as a causative factor in the hamstring strain injury (Garrett 1990). Recently it has been reported that existing soccer training methods and soccer match play develops the knee musculature towards quadriceps dominance (Iga *et al.,* In press) and soccer match play leads to a reduction in the hamstrings to quadriceps ratio (Rahnama *et al.,* 2003; Greig, 2008), both these findings imply that soccer training and match play leads to a relative weakness of the hamstrings muscles. Also, during the running action it has been proposed that the microscopic damage to muscle caused by eccentric actions may lead to the occurrence of hamstrings injuries (Brockett *et al.,* 2004).

Eccentric muscle actions cause damage to muscle (McHugh *et al.,* 1999); this muscle damage is thought to occur as a result of non-uniform lengthening of individual sarcomeres (Morgan, 1990). It has been hypothesised that this initial damage occurs beyond the optimal length of the muscles' length tension relation (Brockett *et al.,* 2004). This initial injury could manifest into a more serious hamstring strain injury late in the game or training session due to repetitive eccentric hamstrings actions during activities like running. Support for this theory can be found in reports of a higher incidence of hamstrings injuries towards the end of matches and training sessions (Woods *et al*., 2004; Brooks *et al*., 2006).

However, surprisingly laboratory based studies have reported that eccentric actions appear not to be as influenced by muscle fatigue as other types of muscle actions (Tesch *et al.,* 1990; Pull and Ranson, 2007). This is even more surprising when you consider that during eccentric actions there is a preferential recruitment of low endurance, high threshold motor units (Tesch *et al.,* 1990).

An explanation for this phenomenon is the added mechanical advantage of lengthening actions, such as greater absorption and storage (Lastayo *et al.,* 2003). This is suggested to lead to eccentric actions being more efficient compared to concentric and isometric actions. In addition, less motor units are recruited during eccentric actions compared to concentric and isometric actions (Tesch *et al.,* 1990). This theory is confirmed as increases in oxygen consumption are insignificant in eccentric action in comparison to isometric or concentric actions (Dudley *et al.,* 1991), and a relatively low ATP turnover and a reduced production of lactate during eccentric actions compared to concentric actions have been reported (Ryschon *et al.,* 1997; Horstmann *et al.,* 2001). These findings would suggest that eccentric actions are less susceptible to fatigue when compared to concentric and isometric actions.

However studies have reported strength impairments following eccentric exercise. These strength impairments manifest into disturbances in force production (Pull and Ranson, 2007). This force reduction has been attributed to factors such as excitation-contraction coupling impairment, mechanical adaptations within the muscle (sarcomergenesis), an increased susceptibility to damage of fast twitch fibres, and impaired glycogen resynthesis (Bryne *et al.,* 2004). As it appears that most muscle damage occurs during eccentric actions when the muscle is fatigued it is logical to train an athlete under these conditions to prevent future muscle damage.

It has been suggested that resistance training to increase the eccentric strength of the hamstring muscle group may improve this muscle group's capability to absorb kinetic energy prior to failure, attenuating the risk of a muscle strain injury (Stanton and Purdam, 1989). The principles of training specificity indicate that muscle specifically adapts to the mechanical and metabolic stresses to which it is exposed (Baechle, 2000). Therefore, to induce neuromuscular adaptation in the eccentric strength of muscle, resistance training methods that emphasise an eccentric action should be utilised. Logistically, exercising with maximal voluntary eccentric action is by no means an easy feat (Hortobagyi, 2003). Training using traditional free-weights and machine-weights involves the performance of alternating concentric (muscle shortening) and eccentric (muscle lengthening) muscle actions. It is assumed that by performing the eccentric component of the movement at a deliberately slow velocity the exposure of muscle to an eccentric stimulus may be increased and this may serve as a stimulus for developing eccentric muscle strength. However, this method of training is yet to receive scientific validation, and providing an optimal training overload may prove difficult (Hortobagyi, 2003). Specialist training devices initially designed for resistance training in micro-gravity have been developed (Berg and Tesch, 1992). Although excellent results in terms of injury prevention and improved sprint performance have been reported following training using such devices

(Askling *et al.,* 2002), these training machines are relatively expensive; consequently, their cost of purchase may prove prohibitive in many contexts. Another specialist device often used to train muscles eccentrically is an isokinetic dynamometer. Similarly, training using these devices may not be available to many soccer clubs and may prove impractical to perform with large numbers of individuals. Hence field-based training methods may be of more practical use at professional soccer clubs.

The 'Nordic' hamstrings exercise (NHE) has received increasing interest in recent years as a means of training to increase the eccentric strength of the hamstrings (Brughelli and Cronin, 2007). When performing the NHE a trainee starts in a knelt position with their ankles secured by a partner. Whilst maintaining their hip joint in an extended position, the trainee must then resist a forward-falling motion by engaging the hamstring muscles. The main attraction of this exercise is that it requires no additional equipment and can be performed simultaneously by a squad of players in the "field". Training time at professional clubs is often limited and coaches may be reluctant to redirect time away from technical and tactical training for specific resistance training (Iga *et al.,* In Press). Therefore, an additional advantage of the NHE is that this exercise can be incorporated into a warm-up routine; consequently, time utilised for technical and tactical training should not be jeopardised.

Electromyography has confirmed that the NHE is the optimal hamstrings field based exercise for motor unit recruitment, compared to other exercises commonly proscribed for training the hamstrings (Ebben *et al.,* 2006). Additionally, both an increase in hamstrings eccentric strength (Mjølsnes *et al.*, 2004) and modifications in the length-tension relations of the hamstrings muscles to longer muscle lengths have been reported after a period of training with the NHE (Brockett *et al.,* 2001; Clark *et al.*, 2005). Increasing the hamstrings eccentric strength may correct existing muscle imbalances about the knee, and increasing the hamstrings muscles' working range of motion relative to its length-tension relation may provide protection against initial micro-damage caused by eccentric actions, by preventing fibres from reaching a length where they are susceptible to initial damage and a subsequent tear (Proske and Morgan, 2001). In support of this, one group of researchers reported a significant reduction in the incidence and severity of hamstring injuries following the incorporation of this exercise into the existing strength training routines of professional rugby union players (Brooks *et al.,* 2006).

Despite this, Brughelli and Cronin, (2007) suggested that due to the bilateral nature of this exercise, when this exercise is incorporated into a training programme the stronger limb may compensate for the weaker limb; over time this may induce or exacerbate existing bilateral strength asymmetries, possibly predisposing the weaker limb to injury (Knapik *et al.,* 1991). However, this suggestion has yet to be examined through eccentric isokinetic strength assessments. Brughelli and Cronin, (2007) also questioned the ability of the NHE to engage and thus train the hamstring muscles at more extended knee angles. This is the knee angle where most hamstring injuries are reported to occur, late in the forward swing phase of the running action as the hamstring muscle group works eccentrically (i.e., lengthens whist generating tension) to prevent hyperextension of the knee and flexion of the hip (Garrett, 1996), likewise, this postulate has also yet to be examined. To date no research group has systematically evaluated the recruitment characteristics of the hamstrings muscles during the NHE. Additionally, no research group has examined whether bilateral strength asymmetries are present following a training programme incorporating the NHE. Also, eccentric training appears not to be velocity specific (Shepstone *et al.,* 2005); no research group has investigated this phenomenon with a training programme incorporating the NHE.

Aims and objectives

Therefore, the aims of this thesis are to:

1. Examine the neuromuscular recruitment characteristics of the hamstrings muscle group at various knee joint positions during the NHE.
2. Examine if bilateral strength asymmetries between limbs are present following a resistance training programme incorporating the NHE.
3. Examine if eccentric training with the NHE results in velocity specific adaptations.

These aims are underpinned by the following objectives: -

1. Electromyography data from the hamstrings muscle group will be collected during the performance of the NHE. Comparisons will be made between limbs and through the range of motion of the movement.

2. Isokinetic hamstrings peak torque data will be compared between limbs prior to and following a training programme incorporating the NHE to investigate if asymmetries are present.

3. Isokinetic hamstrings peak torque data will be collected from a range of angular velocities to investigate if training with the NHE results in velocity specific adaptations.

CHAPTER II

Review of Literature

2.1 Introduction

The first section of this chapter reviews the literature on the incidences and location of soccer injuries and what affect this has on players and professional clubs. This is followed by a section reviewing the literature on the aetiology of hamstrings strain injuries and the recent advances in the understanding of this type of injury. Finally, this chapter will review the literature on the role resistance training plays in the prevention of hamstrings strain injuries, focusing specifically on eccentric based training.

2.2 Incidence of injury

Due to the high physical demands put on soccer players (Reilly, 1996) it is not a surprise that the sport of soccer is associated with a relatively high injury rate (Hawkins and Fuller, 1999). A soccer injury has been defined as any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activity (Fuller *et al.,* 2006). In this definition an injury that results in a player receiving medical attention is referred to as a 'medical attention' injury and an injury that results in a player being unable to take part in future training or matches is called a 'time loss' injury. The majority of studies adopt the second sub-group of this definition and report injuries that are sustained during a scheduled training session or match which cause a player to miss the next training session or match (Hagglund, 2005a). Using this definition injury incidences have been shown to vary between male and female soccer players, with female soccer players sustaining more injuries overall and during training sessions (Wong and Hong, 2005). This has been attributed to the increased susceptibility of female athletes to knee injuries, especially to the anterior cruciate ligament (Roos *et al.,* 1995; Shea *et al.,* 2004). This is due to the variation in joint laxity and anterior cruciate ligament geometry between male and female athletes (Quatman *et al.*, 2008). It has also been reported that there is a difference between the amount of reported injuries sustained between indoor and outdoor soccer, with the incidences of injuries outdoors almost twice that of indoors (Keller *et al.*, 1987). Based on these differences, the remainder of this review will only consider the findings from studies reviewing outdoor soccer played by male participants.

The overall level of injury to professional soccer players has recently been shown to be around 1000 times higher than that for industrial occupations such as construction and mining which are generally regarded as high risk (Hawkins and Fuller, 1999). In addition, it has recently been reported that the level of injury incidences within professional soccer are considerably higher when compared to most other team sports (Junge *et al.*, 2004). Furthermore, following the analysis of two successive population surveys based on sports injuries in the Netherlands, using a broad subjective definition for a sports injury, it has been estimated that 30% of all sports injuries were soccer related (Inklaar *et al.*, 1995). This equates to 800,000 injuries being sustained in the Netherlands between 1987 and 1992 due to the sport of soccer (Inklaar *et al.*, 1995). Additionally, during a prospective study in Sweden where injury was defined as actually visiting a physician due to an acute injury sustained whilst playing sport, soccer was identified as the fourth most likely of seventeen sports to report an injury incident (De Loes, 1988).

The incidence of injury can be quantified by the number of injuries sustained per hours of exposure time (Hagglund *et al.*, 2005a). The incidence of injuries amongst senior male professional soccer players has been estimated to range between 25 and 35 per 1000 game hours (Hawkins and Fuller 1999; Morgan *et al.*, 2001; Junge *et al.*, 2004; Hagglund *et al.*, 2005b). Likewise the injury incidences at the most competitive level of club (UEFA Champions League) and international soccer have been reported to be 30.5 injuries per 1000 competitive game hours (Walden *et al.,* 2005) and in the Swedish national team to be 30.3 injuries per 1000 hours competitive game time (Ekstrand *et al.,* 2004). Recently, these epidemiological studies reporting the incidence of soccer injuries (Hawkins and Fuller 1999; Morgan *et al.,* 2001; Ekstrand *et al.,* 2004; Junge *et al.,* 2004; Hagglund *et al.,* 2005b; Walden *et al.,* 2005) have been criticised for having fundamental differences in their definitions of how time exposure is calculated (Fuller *et al.,* 2006). It is well documented that variations in definitions and methodologies create significant differences in the results and conclusions obtained from studies of sports injuries (Fuller *et al.,* 2006). To evaluate the injury risk for a certain sport the exposure factor needs to be considered. This is usually displayed by the number of injuries per 1000 hours of exposure time (Hagglund *et al.,* 2005a); ideally this should be done by recording the amount of exposure time for each individual, but is often done through estimations based on attendances during training sessions and games (Hagglund *et al.,* 2005a).

Despite this variation in how time exposure is calculated there is conclusive evidence that more injuries are sustained per 1000 hours of exposure time during game situations when compared to training sessions (Engestrom *et al.,* 1990; Hawkins and Fuller, 1999; Morgan *et al.,* 2001; Ekstrand *et al.,* 2004; Walden *et al.,* 2005; Wong and Hong*.,* 2005). It has been reported that the injuries per 1000 hours of exposure time for senior soccer players was between 2.9 and 3.5 during training and between 13 and 35.3 during game time respectively (Engestrom *et al.,* 1990; Hawkins and Fuller, 1999; Morgan *et al.,* 2001). This suggests that the competitive nature of a game situation increases the risk of a player sustaining an injury. Likewise, the injury incidences during international soccer and at the most competitive level of club soccer (UEFA Champions League) show a similar trend towards a higher reported injury incidence in a game situation compared with training, with 5.8 injuries per 1000 training hours training time and 30.3 and 30.5 injuries per 1000 competitive game hours respectively (Ekstrand *et al.,* 2004; Walden *et al.,* 2005). Interestingly, the incidence of injuries in training is slightly higher at the most competitive levels of soccer (Ekstrand *et al.,* 2004; Walden *et al.,* 2005). The authors described this increase as the result of more competition for playing positions at the top clubs and at international level making the players more competitive during training. Despite this higher prevalence of injuries during training at the top level, the level of injuries during game situations appears to plateau at around 30 injuries per 1000 hours exposure (Hawkins and Fuller, 1999; Ekstrand *et al.,* 2004; Walden *et al.,* 2005). Interestingly many authors have also reported a trend for more injuries to be reported at the end of each half and later in a game (Hawkins and fuller 1999; Hawkins *et al.,* 2001; Junge *et al.,* 2004, Yoon *et al.,* 2004; Woods *et al.,* 2004), implying that fatigue may influence the occurrence of an injury. The high incidence of injury in the senior professional game is broadly mirrored in youth soccer. Two early epidemiological studies investigated injuries within adolescent team sports and concluded that soccer was in the top four most likely sports to cause injury (Backx *et al*., 1991; De Leos, 1995). Specifically within junior soccer it has been reported that 4.1 injuries per 1000 hours training time and 37.2 injuries per 1000 hours game time were sustained (Hawkins and Fuller, 1999). The slightly higher incidences of injury during game time compared to the senior game has been explained by youth players spending more of their time playing in games and less time training than the senior players (Hawkins and Fuller, 1999). However, in contrast to the findings of Hawkins and Fuller, (1999), it has been reported that in a 10 season study at the most elite level of junior soccer in France that a total of 4.8 injuries per 1000 hours exposure time were recorded and 11.2 and 3.9 injuries per 1000 hours for games and training, respectively (Le Gall *et al.,* 2006). This suggests that the incidence of soccer related injuries appear to be less in junior soccer compared to the senior game.

An early study which reviewed 2 junior and 4 senior epidemiological studies from the US and Europe concluded that soccer injury rates increase with age, with senior and professional players sustaining 15 to 30 times as many injuries as junior players (Keller *et al.,* 1987). Additionally, more recently it has been reported that the injury incidences at youth academy level are approximately half that of the senior professional game (Price *et al.,* 2004). Data obtained from the 38 English academy clubs over two competitive seasons reported that, on average 0.4 players per season were injured and on average 21.9 days of training were missed due to an injury, with on average 2.31 games missed per injury (Price *et al.,* 2004). Data obtained from 91 senior professional football clubs over two competitive seasons (1997-1999) reported that the average injury rate within professional senior soccer was higher at 1.3 players per season, with on average 24.2 days training missed due to an injury, with on average 4 games missed per injury (Hawkins *et al.,* 2001). These data also suggests that the incidence and time lost related to injuries appear to be more frequent and severe in the senior professional game. The reason for this has been suggested to be that most academy players have much less exposure time to sustain an injury, as players up to the age of 17 usually only train twice a week and play at weekends (Price *et al.,* 2004).

Despite the frequency and the time lost because of an injury appearing to be less in junior soccer, the issue of absence from training and competitive matches has to be considered from a different viewpoint at youth academy level as player development and skills acquisition are of up-most importance at this stage of the player's career (Price *et al.,* 2004). At youth academy level on average each injury stops the player participating in normal activities for 21.9 days, and each player is injured on average 0.4 times per season (Price *et al.,* 2004). This equates to the player missing about 6% of the season and consequently a large portion of his development (Price *et al.,* 2004). It has been hypothesized that a player must practice slightly over 3 hours a day for ten years to achieve maximal skill development (Ericsson *et al.,* 1994). This figure would be hard to achieve if 6% of a players time was lost through injury (Price *et al.,* 2004).

In professional soccer, the impact of a players injury to the club can be measured by the number of competitive matches missed (Price *et al.,* 2004). During two seasons (2003-2005) individual absences at an English division one soccer club from either training or a competitive game were documented on a comprehensive daily register (Parry *et al.,* 2006). An absence was defined as the unavailability to train or play in a competitive game irrespective of reason. Absentees totaled 378 for first team matches and 1441 for training sessions. Of these absentees, reportable injuries accounted for 49% of first team match unavailability and 60% of training sessions missed (Parry *et al.,* 2006). These results indicate that the single biggest factor for a soccer player's absence is a soccer-related injury (Parry *et al.,* 2006). First team player's absences may lead to a reduced club income due to reduced match attendances, and diminishing prize money as a result of low league position, and early cup competition exits (Woods *et al.,* 2002). Additionally, absentees due to injury can be evaluated against the cost of a player's wages (Price *et al.,* 2004). The Premier League clubs total wage costs alone was predicted to exceed £1 billion for the first time in 2007/08 (Jones, 2007). Given that 10% of all squads were unavailable to train each week because of injury (Hawkins *et al.,* 2001) the projected financial loss in squad members wages due to injury for that season was £100 million. In addition, the cost of an injury to a club could be included in the form of medical fees and increased insurance premiums (Woods *et al.,* 2002). Consequently, efforts must be made not only to prevent injuries occurring but also to rehabilitate players sufficiently following injury.

2.3 Location of injury

Numerous studies have reported that the majority of soccer related injuries occur at the lower extremity (Wong and Hong, 2005). Expressed as a percentage of total injuries, it is generally reported that between 65-90% of all injuries in youth soccer players (Elias, 2001; Junge *et al.,* 2003; Price *et al.,* 2004) and between 85-95% of all soccer injuries in senior soccer players (Elkenstrand and Gillquist, 1983; Nielsen and Yde, 1989; Yde and Nielsen, 1990; Hawkins and Fuller 1999; Hawkins *et al.,* 2001) occur at the lower extremity. The high proportion of lower extremity injuries in soccer has been attributable to the nature of the sport and the high demands placed on the lower extremity. There is evidence of a predominance of injuries to the dominant limb (Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Price *et al.*, 2004). This phenomenon may be attributed to the preferential use of the dominant limb in activities such as kicking, jumping and tackling, therefore increasing injury risk (Rahnama *et al.,* 2003).

Early epidemiological studies reported that the ankle was the location for the highest incidences of injuries in soccer players (Prichett, 1981; Nielsen and Yde, 1989; Engstrom *et al.,* 1991), although more recently the thigh has consistently been reported to be the major site for injury in soccer players (Kibler, 1993; Inklaar, 1996; Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Woods *et al.*, 2002; Price *et al.*, 2004; Junge *et al.,* 2004; Hagglund *et al.,* 2005b; Walden *et al.,* 2005). This apparent change could be due to the increase in physical demand put upon players in activities such as running and sprinting in the modern game (Reilly, 1996). This phenomenon is supported by the fact it has been reported that the high proportion of injuries at the thigh can be explained by the high incidence of muscle strain injury, particularly to the hamstrings muscle group (Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Woods *et al.*, 2002; Price *et al.*, 2003). Video analysis of the hamstrings strain injury has revealed that the injury is typically sustained during running activities (Verrall *et al.,* 2005), late in the forward swing phase of the running action as the muscle group works eccentrically (i.e., lengthens whist generating tension) to prevent hyperextension of the knee and flexion of the hip (Garrett, 1996). This observation is confirmed by the literature where there is no reported difference in the incidence of hamstrings injury between the dominant (DOM) and non-dominant (NDOM) limbs (Woods *et al.,* 2004), suggesting that during the running action both limbs are susceptible to a hamstrings strain injury (Woods *et al.,* 2004). Biceps femoris appears to be the most commonly injured hamstrings muscle (Woods *et al.,* 2004). The reason for this is suggested to be because of the bi-articular make up of this muscle (Coburn, 2002), as during activities like sprinting the bi-articular biceps femoris muscle has to cope with high internal forces and rapid changes in muscle length and mode of muscle action (Pull and Ranson, 2007). The biceps femoris has been reported to account for 53% of all reported cases of hamstrings strain injuries (Woods *et al.,* 2004). Hamstrings injuries have also been reported to be localised at the myotendinous junction (Safran *et al.,* 1988; Garrett, 1996). It is possible that the oblique arrangement of the muscle's fibres in this region may reduce their ability to withstand high tensile forces (Noonan and Garrett, 1992), rendering them prone to damage.

During a two season period (1997 – 1999) the single highest figure reported within 91 professional clubs for the location of an injury was the thigh; 23% of all injuries were reported in this location (Hawkins *et al.,* 2001). Of these thigh injuries, 81% were muscle strains, and 67% were in the hamstrings region (Hawkins *et al.,* 2001). There is a similar trend for the location of an injury within soccer youth academies, where 19% of all injuries occurred in the thigh; of these thigh injuries 79% were classified as strains and 57% of the strains in the thigh were reported to be in the hamstrings muscle group (Price *et al.,* 2004). Specifically, the Football Association Medical Research Programme quantified that 12% of all injuries reported from 91 professional clubs over a two season period (1997-1999) were hamstrings strains (Woods *et al.,* 2004). A total of 796 hamstring injuries were reported, this being more than any other muscle group (Woods *et al.,* 2004). There was a trend for an increase in reported hamstring injuries in the higher leagues (Woods *et al.,* 2004), confirming that more injuries occur at the more competitive levels of football

(Engestrom *et al.,* 1990; Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Morgan *et al.,* 2001; Walden *et al.,* 2005). The total number of days that players were absent over the two-season period due to a hamstrings strain was 13,116, and a total of 2029 games were missed, giving an average of 18 days and 3 games missed per hamstrings strain injury (Woods *et al.,* 2004). A total of 5 hamstring strains per club per season were reported; this resulted in 15 matches and 90 days missed per club per season (Woods *et al.,* 2004).

2.4 Summary of epidemiological studies

Current research suggests that the overall level of injury within soccer is unacceptable when compared to other industrial occupations and other team sports (Hawkins and Fuller, 1999; Junge *et al.,* 2004). The incidence of injuries is higher within the senior professional game than the junior game (Hawkins *et al.,* 2001, Price *et al.,* 2003). More competitive game situations and training sessions contribute to an increase in injury incidence (Engestrom *et al.,* 1990; Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Morgan *et al.,* 2001; Walden *et al.,* 2005) and more injuries are sustained later in halves and games (Hawkins and fuller 1999; Hawkins *et al.,* 2001; Junge *et al.,* 2004, Yoon *et al.,* 2004; Woods *et al.,* 2004), suggesting fatigue may contribute to the susceptibility of an individual to injury. The single biggest factor contributing to the absence of a professional football player from a competitive game or training session is a soccer related injury (Parry *et al.,* 2006). Player absentees at the professional level can lead to a huge financial loss to the professional clubs (Woods *et al.,* 2002; Price *et al.,* 2004). Absentees at youth academy level leads to time lost because of injury, which can substantially effect a player's development (Price *et al.,* 2004). Recently the thigh has been consistently reported as the major site for injury (Nielsen and Yde, 1989; Kibler, 1993; Inklaar, 1996; Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Woods *et al.*, 2002; Price *et al.*, 2004; Junge *et al.,* 2004; Hagglund *et al.,* 2005b). This high proportion of injuries at the thigh is explained by the high incidence of muscle strain injury, particularly to the hamstrings muscle group

(Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Woods *et al.*, 2002; Price *et al.*, 2003). Consequently, implementing a programme that can prevent strains to the posterior thigh in soccer players would serve to increase player's availability and, as a result at the professional level, improve club success and increase clubs revenue. At youth academy level a similar programme would improve the development of players through an increase in time for enhancement of skills.

2.5 Aetiology of hamstring injuries

Despite an expanse of literature dedicated to the aetiology of the hamstrings strain injury (reviews Worrell, 1994; Croisier, 2004), the exact cause is still unclear. A variety of factors have been implicated (Croisier, 2004); the most plausible traditional suggestions and the recent advances in the understanding of the hamstrings strain injury are discussed in the following section.

2.6 Traditional suggested contributing factors

Traditionally suggested factors for the hamstrings muscle strain include an inadequate or lack of warm-up, inadequate stretching, poor fitness level and inadequate training modalities, fatigue, poor flexibility and previous injury (Croisier, 2004).

The warm up is the unavoidable stage that occurs at the beginning of a sports session; this facilitates an increase in connective tissue extensibility, which is temperature dependent (Garrett, 1996). As a result of this increase in muscle temperature the muscle can stretch more and absorb more force before failure (Safran *et al.,* 1988). Therefore a warm-up before exercise seems critical because of the capability of the musculotendinous unit to absorb energy is directly proportional to both resting length and muscle temperature (Safran *et al.,* 1988). The implementation of a structured warm-up designed to increase muscle temperature, with the emphasis on awareness of knees and ankles during standing, running, cutting, jumping and landing, led to a reduction in reported knee and ankle injuries in youths playing sports (Olsen, *et al.,* 2005). This suggests that a structured warm-up serves to increase the resting length and temperature of muscle, which increases the amount of force the muscle can absorb. Increasing the amount of force the muscle can absorb may reduce the incidences of reported injuries.

It has long been recommended that participants stretch before exercise, this belief is based on the notion that a 'tight' muscle unit is less compliant, which may increase the risk of injury. Despite this, there is empirical evidence that stretching before exercise does not reduce the risk of injury (Shrier, 1999; Herbert and Gabriel, 2002; Witvrouw *et al.,* 2004). Inadequate pre-season training resulting in low fitness levels, which ultimately leads to the early fatigue of muscles, has been suggested to contribute to increased injury rate during the season (Hawkins *et al.,* 2001). Fatigue is frequently suggested as a contributor to hamstrings injuries (Garrett, 1996); as epidemiological evidence in soccer indicates hamstrings strains regularly occur at the end of each half and later in the game (Hawkins and fuller 1999, Hawkins *et al.,* 2001; Junge *et al.,* 2004; Yoon *et al.,* 2004; Woods *et al.,* 2004). Research into rabbits' muscles has showed that fatigue results in the amount of energy absorbed by the fatigued muscle to be reduced (Mair *et al.,* 1996). Also within soccer, running or sprinting is the single activity that contributes most to a hamstrings strain injury (Price *et al.*, 2003; Woods *et al.,* 2004; Verrall *et al.,* 2005). The action of running is a multi-segmental action, which requires co-ordination between the proximal (thigh) and distal (shank) (Putnam, 1991). The presence of fatigue during multi-segmental tasks can result in alterations in muscle activation patterns (Forestier *et al.,* 1998; Huffens *et al.,* 2006). In particular, the dual innervation of biceps femoris could lead to asynchrony in the activation of separate parts of the muscle and result in inefficiencies (Croisier, 2004). This situation amplifies fatigue and could predispose the athlete to subsequent injury (Croisier, 2004).

Soccer specific protocols designed to mimic the intensities of soccer match play have been utilised to fatigue muscles similarly to that of a game situation (Drust *et al.,* 2000; Nicholas *et al.,* 2000). It has been reported that soccer specific fatigue leads to a reduction in the both the conventional (hamstrings concentric peak torque production in relation to the quadriceps concentric peak torque production) hamstrings to quadriceps ratio (Rahnama *et al.,* 2003), and more recently, to the functional (hamstrings peak eccentric torque in relation to the quadriceps peak concentric torque) hamstrings to quadriceps ratio (Greig, 2008). Interestingly, it has also been reported that the functional hamstrings to quadriceps ratio was not only reduced at the end of the game relative to the first 15 minutes but also in the first 15 minutes following the half time interval (Grieg 2008). These findings are in accordance with epidemiological studies, which have reported an increase in reported injuries at these specific times (Hawkins and fuller 1999; Hawkins *et al.,* 2001; Junge *et al.,* 2004; Yoon *et al.,* 2004; Woods *et al.,* 2004). This evidence suggests that muscle fatigue representative of soccer match play may be a factor in the development of a hamstrings injury; not only because it reduces the hamstrings to quadriceps ratio, which has been suggested as a predictor of a players susceptibility to a hamstrings strain injury (Croisier *et al.,* 2008), but also it may lead to alterations in muscle activation patterns specifically to the biceps femoris muscle, the muscle where most hamstrings injuries occur (Woods *et al.,* 2004).

However, surprisingly laboratory based studies have reported that eccentric actions appear not to be as influenced by muscle fatigue as other types of muscle actions (Tesch *et al.,* 1990; Pull and Ranson, 2007). This is even more surprising when you consider that during eccentric actions there is a preferential recruitment of low endurance, high threshold motor units (Tesch *et al.,* 1990).

An explanation for this phenomenon is the added mechanical advantage of lengthening actions, such as greater absorption and storage (Lastayo *et al.,* 2003). This is suggested to lead to eccentric actions being more efficient compared to concentric and isometric actions. In addition, less motor units are recruited during eccentric actions compared to concentric and isometric actions (Tesch *et al.,* 1990). This theory is confirmed as increases in oxygen consumption are insignificant in eccentric action in comparison to isometric or concentric actions (Dudley *et al.,* 1991), and a relatively low ATP turnover and a reduced production of lactate during eccentric actions compared to concentric actions have been reported (Ryschon *et al.,* 1997; Horstmann *et al.,* 2001). These findings would suggest that eccentric actions are less susceptible to fatigue when compared to concentric and isometric actions.

Studies have reported strength impairments following eccentric exercise. These strength impairments manifest into disturbances in force production (Pull and Ranson, 2007). This force reduction has been attributed to factors such as excitation-contraction coupling impairment, mechanical adaptations within the muscle (sarcomergenesis), an increased susceptibility to damage of fast twitch fibres, and impaired glycogen resynthesis (Bryne *et al.,* 2004). As it appears that most muscle damage occurs during eccentric actions when the muscle is fatigued it is logical to train an athlete under these conditions to prevent future muscle damage.

The view of some authors is that a lack of flexibility has not been conclusively linked to a risk of hamstrings injuries (Devlin, 2000; Rolls *et al.,* 2004). In fact, it has been argued that poor flexibility could be a consequence of muscle injury rather than a cause of muscle injury (Rolls *et al.,* 2004). However, it has been proposed that soccer players with an increased tightness of the hamstrings have a statistically higher risk of developing a lesion on that muscle group (Witvrouw *et al.* 2003). Interestingly, it has been shown that an imbalance in range of motion between the left and right limbs, led to a 1.7 times more likely chance of experiencing a strain or sprain injury compared to a more balanced range of motion (Knapik *et al.,* 1991). There is also experimental evidence in humans to suggest an association between flexibility and muscle injury (McHugh *et al.,* 1999). Exercise involving predominantly eccentric actions frequently causes muscle damage, resulting in delayed onset muscle soreness (McHugh *et al.,* 1999). Passive muscle stiffness plays a key role in delayed onset muscle soreness symptoms; this phenomenon can possibly be explained by tendon-aponeurosis (McHugh *et al.,* 1999). Active lengthening of a stiff muscle whilst the tendon is rigid could result in myofibrillar strain; conversely, the tendon of a compliant muscle would be able to partially absorb lengthening, which may limit myofibrillar strain (Croisier, 2004). However, the symptoms of delayed onset muscle soreness do not manifest until 24 hours post exercise; therefore this theory does not explain hamstrings strain injuries that occur during matches or training sessions, unless eccentric exercise was performed in the days preceding the game or training session in which the injury was sustained. An imbalance in the range of motion (flexibility) between limbs has been suggested to increase the risk of injury (Knapik *et al.,* 1991), implying that flexibility may contribute to an increase in the occurrence of hamstrings injuries. Also, in activities that are predominantly eccentric (i.e. the hamstrings during running and sprinting), the symptoms of DOMS include an increase in muscle stiffness (flexibility); these symptoms may lead to an increase in hamstrings strain injury as less of the muscle is able to absorb lengthening due to an increase in the muscles stiffness (flexibility).

Previous injury has also been shown to be associated with an increase in injury rate within both junior (Kucera *et al.,* 2005) and senior (Hagglund *et al.,* 2006) levels of soccer. The reoccurrence rate of hamstrings strains in soccer players has been shown to be relatively high compared to the reoccurrence of other reported injuries (Woods *et al.,* 2004). These findings question the efficacy of current rehabilitation programmes consisting of rest, cryotherapy, anti-inflammatory drugs, compression, elevation and physical therapy (Noonan and Garrett, 1999) for preventing further hamstrings strain injuries. Hamstrings strain injuries are typically sustained during running activities (Verrall *et al.*, 2005), late in the forward swing phase of the running action as the hamstrings muscle group works eccentrically (Garrett, 1996). This suggests that training methods designed to strengthening the hamstrings during eccentric actions may be a more appropriate method to prevent or rehabilitate an individual from a hamstrings strain injury.

2.7 Recent advances

Recent advances in the understanding of factors that may contribute to the aetiology of hamstrings strain injuries suggest that a weakness in the eccentric strength of the hamstrings, and by virtue the reciprocal muscle strength balance between the quadriceps and hamstrings about the knee, and the length tension relationship of the hamstrings muscle group, may be more realistic determinant of a participants susceptibility to a hamstrings strain injury.

The ratio of maximal isokinetic hamstrings muscle strength relative to maximal isokinetic quadriceps muscles strength is a measure of the muscle strength properties about the knee (Baltzopoulos and Brodie, 1989). Early epidemiological studies using the conventional method of assessing the strength properties about the knee concluded that hamstrings strains were significantly associated with a low hamstrings to quadriceps ratio of peak torque production on the injured limb (Knapik *et al.,* 1991; Orchard *et al.,* 1997). Recently a more accurate way of reporting the hamstrings to quadriceps ratios has been developed; this ratio is called the functional hamstrings to quadriceps ratio (Dvir *et al.,* 1989; Aagaard *et al.,* 1995). In the functional hamstrings to quadriceps ratio if the hamstrings eccentric peak torque is equal to the peak concentric quadriceps torque then the ratio is 1:1; if the quadriceps are stronger, then the ratio will be less than 1; a ratio of less than one is hypothesised to lead to a increased risk of injury (Hughes *et al.,* 2006). An early study using the both the conventional and functional assessment of hamstrings to quadriceps ratio reported that a low hamstrings to quadriceps strength ratio was not related to hamstrings strain injuries (Bennell *et al.,* 1998). More recently it has been identified that the functional assessment of hamstrings to quadriceps ratio was highly specific, when compared to the conventional assessment, in identifying players at risk for injury, with 187 of 216 players showing an imbalance in this strength assessment (Croisier *et al.,* 2008).

Interestingly, more recent studies have not only used both concentric and eccentric isokinetic testing to determine whether strength asymmetries could be a predictor for future hamstrings strain injuries, but also monitored the effectiveness of rehabilitation programmes designed to correct muscle imbalances between the hamstring and quadricep muscles (Croisier *et al.,* 2002; Croisier *et al.,* 2008). Croisier *et al.* (2002) identified 18 subjects who were found to have strength deficits, in either between limbs or in hamstrings to quadriceps ratios. Where imbalances were present, subjects followed 10 to 30 further sessions specifically designed to correct imbalances. No further hamstring injuries were sustained in the subjects who were corrected for imbalances in the following 12 months. Likewise, in a second study by the same author (Croisier *et al.,* 2008) 462 players were assessed for strength imbalances; 216 players with preseason abnormalities in either bilateral or hamstrings to quadriceps ratio were identified. Of the 462 players assessed, 35 hamstrings strain injuries were recorded. The rate of hamstrings muscle injury was significantly higher in the players with untreated strength imbalances in comparison to players showing no strength imbalances in preseason. Also normalising the isokinetic muscle imbalances through training programmes, incorporating both concentric and eccentric modes of training at different angular velocities depending on the weakness of the individual (Croisier *et al.,* 2002), reduced the risk factor for a hamstrings strain injury in the forth coming season. This suggests that outcomes of isokinetic strength testing can be a predictor of a players susceptibility to a hamstrings strain injury, and training designed to rehabilitate imbalances can reduce the likelihood of a future injury.

The majority of training at professional clubs is dedicated to tactical and technical aspects of the game, and therefore limited time is dedicated to increasing muscle strength through resistance training (Iga *et al.,* In press). It has been suggested that a weakness in eccentric strength of the hamstrings muscles might cause hamstrings strain injuries (Stanton and Purdam, 1989). Recently it has been reported that muscle loading patterns during soccer training and match-play may asymmetrically develop the strength of the knee joint muscles in favour of quadriceps dominance (Iga *et al.,* In Press). The finding from this investigation suggests that the muscle loading patterns experienced during soccer may negatively alter the reciprocal balance of strength between the hamstrings and quadriceps muscles for knee extensions performed at high velocity (Iga *et al.,* In Press). This implies that traditional training methods adopted at professional clubs, with the emphasis on technical and tactical skills development without compensatory resistance training, may contribute to an increase in the susceptibility of a player to a hamstrings strain injury.

It is when high velocity knee extension movements, identified by Iga *et al.* (In Press) to be where the reciprocal balance of the hamstrings and quadriceps may be negatively altered due to the muscle loading patterns of soccer match play, are performed during maximal velocity running that most hamstrings strain injuries occur (Price *et al*., 2004; Woods *et al.,* 2004; Verrall *et al.,* 2005). It has also been demonstrated that during a running cycle the EMG activity is greatest during the late swing phase (Jonhagen *et al.,* 1996), and it is during the late swing phase of the running action that the hamstrings are contracted eccentrically (Garrett, 1996). Therefore, hamstrings strains are thought to occur during maximal running whilst the hamstrings are performing an eccentric action, and low hamstring strength has been identified as a risk factor (Arnason *et al.,* 2006). Advances have implicated the microscopic damage to muscle caused by eccentric actions in the occurrence of a hamstrings strain injuries (Brockett *et al*., 2004). It is well documented that eccentric muscle actions cause damage to muscle (McHugh *et al.,* 1999). Muscle damage may occur as a result of non-uniform lengthening of individual sarcomeres (Morgan, 1990). It is postulated that the initial damage occurs beyond the optimal length, on the descending limb of the muscle's length-tension relation (Brockett *et al*., 2004). It may be that the repeated eccentric muscle actions during running may aggravate an initial injury, leading to a more serious injury late in the game or training session (Brockett *et al.,* 2001; Proske and Morgan, 2001).

Researchers have observed a shift in the optimal angle for eccentric torque production, to more extended joint positions, following specific eccentric resistance-training of the hamstrings (Brockett *et al*., 2001; Clark *et al*., 2005). This shift in the angle for optimal eccentric torque production may be in response to an increase in the number of sarcomeres in muscle fibres following resistance-training (Morgan, 1990). Increasing the series of muscle fibres may allow muscle fibres to operate at longer muscle lengths (Brockett *et al*., 2001), which in turn may increase the working range of motion of the hamstrings relative to the length-tension relation, conferring protection against initial micro-damage by preventing fibres from reaching a length where they are susceptible to initial damage and a subsequent tear (Proske and Morgan, 2001).

Supporting evidence for the inclusion of eccentric based resistance training, whether it be to increase weakness in the eccentric strength of the hamstrings, compensate strength imbalances about the knee, or to modify the length tension relationship of the hamstrings muscle group, is provided by authors who have reported a significant reduction in the incidence and severity of hamstrings injury in professional rugby and soccer players following specific training of the hamstrings muscles during eccentric modes of exercise (Askling *et al.*, 2001; Mjølsnes *et al.,* 2004; Brooks *et al.*, 2006).

2.8 Summary of aetiology

Quantifying the respective role of each of the factors highlighted above as contributors to a hamstrings injury is complicated and is more realistically illustrated as a combination of factors (Croisier, 2004). Recent advances in the aetiology of hamstrings strain injuries suggested that muscle loading patterns during soccer play asymmetrically develops the strength of the knee joint muscles in favour of quadriceps dominance (Iga *et al.,* In Press), and fatigue protocols designed to mimic the intensities of soccer match play have been shown to reduce the hamstrings to quadriceps ratio later in the game (Rahnama *et al.,* 2003; Greig, 2008). Imbalances in a player's hamstrings to quadriceps ratio have been shown to be an indicator in a participant's susceptibility to future hamstrings injuries (Croisier *et al.,* 2002; Crosier *et al.,* 2008). Also, a weakness in eccentric strength of the hamstrings (Stanton and Purdam, 1989) and a reduced working range of motion of the hamstrings muscle, represented by a reduction in the isokinetic optimum torque angle of the knee flexors (Brockett *et al.,* 2001), have been identified as factors contributing to the risk of hamstring strain injuries. This evidence suggests that resistance training to increase the strength of the hamstrings, particularly in an eccentric action, and increasing the working range of motion of the hamstrings is of up-most importance in reducing a soccer player's susceptibility to a hamstrings strain injury. Secondly, identifying players with knee strength abnormalities through pre season assessments and correcting these abnormalities through rehabilitation programmes should be a priority at professional clubs so as to reduce future injuries.

2.9 Electromyography

Electromyography (EMG) is the discipline that deals with the detection, analysis, and use of the electrical signal that emanates from contracting muscles (De Luca, 2006). Within the last 50 years a particular speciality within EMG has been developed called Kinesiological electromyography (Soderberg and Knutson, 2000). The aim of this type of EMG is to study the muscular function and co-ordination of muscles during movement (Clarys and Cabri, 1993).

The following key areas regarding the collection and analysis of electromyography data will be reviewed in the next few chapters

- Skin Preparation
- Electrode Placement
- Normalisation

2.10 Skin Preparation

Surface electrodes are subject to movement which in turn disturbs the electrode and skin equilibrium and so causes a change in the recorded electrode potential (Gleeson, 2001). Electrode gels or pre-gelled electrodes are required to minimise this change by moving the electrode away from the skin so that movement of the skin does not affect the metal-electrolyte junction and the potential is unaltered (Gleeson, 2001). In addition, it is important to prepare the skin before electrode placement. This is required to reduce the impedance at the electrode-skin barrier from external electrical activity and electromagnetic sources (Gleeson, 2001). Light abrasion of the skin is a suggested technique required for skin preparation (Basmajian *et al.,* 1975), although it is generally accepted that when using surface electrodes the minimum skin preparation should be to degrease the skin with acetone or alcohol wipes (Gleeson, 2001).

2.11 Electrode Placement

Electrodes can either be placed upon the skin or within the muscle itself, electrodes that are placed upon the skin are referred to as surface electrodes. Scientists working in the sports or occupational environment prefer to use surface electrodes instead of indwelling electrodes (Clarys, 2000), as indwelling electrodes are considered to be invasive (Clarys and Cabri, 1993), and have limited application in kinesiological EMG as they are primarily designed to measure single muscle fibre activity (Soderberg and Knutson, 2000).

As the most accurate EMG signals are obtained from the muscle belly area (Clarys, 2000), and surface electrodes can be subjected to cross-talk from other electrodes (Basmajian and De Luca, 1985) the placement of the electrode is of up most importance. The first consideration is to place the electrode away from the motor end plate (De Luca and Knaflitz, 1990), which is located at the border of a muscle (Clarys, 2000). Secondly, the electrode should not be placed near or over the myotendonous junction (De Luca, 1997). Thirdly the electrode should not be placed near the lateral border of the muscle as this electrode placement could possibly be effected by cross-talk (De Luca, 1997). Consequently, four main methods are presented that conform to these requirements

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

2.12 Normalisation

Due to the known variability of EMG signal between subjects and trials due to electrode placement and skin preparation a normalisation procedure is required to reduce variability (Yang and Winter, 1984; Clarys, 2000). Normalisation is the process which allows for referencing the EMG data to some standard value, usually by dividing the raw EMG data by a reference value (Soderberg and Knutson, 2000). Unfortunately it is still unknown which is the best figure to use for normalisation, although there have been trends developed in the past few years to use certain methods in certain situation.

It has been suggested to either normalise against the EMG recorded in a pre determined maximum voluntary isometric contraction (MVIC) or against the peak dynamic EMG data collected during the movement of interest (Yang and Winter, 1984; Clarys, 2000; Soderberg and Knutson, 2000). The use of pre determined maximum voluntary isometric contraction (MVIC) is generally accepted in the literature (Soderberg and Knutson, 2000), and is ideal as a figure for reference in static applications (Clarys, 2000). This is due to the figure collected during MVIC being the most reliable when compared to alternative normalisation techniques such as mean or peak dynamic or isokinetic MVC (Burden and Bartlett, 1999; Bolga and Uhl, 2007). However, for dynamic activities the use of MVIC is debatable as recently many authors have reported that the EMG signal recorded in the dynamic activity is higher than that reported in the isometric activity, resulting in figures greater than 100% (Clarys and Cabri, 1993; Clarys, 2000). The literature to date implies that the selection of an appropriate normalisation technique is still based on logic or opinion and therefore is dependent on the author's viewpoint (Soderberg and Knutson, 2000). However based on the suggestions of Clarys and Cabri, (1993) and Clarys, (2000) normalising to the peak EMG activity during the movement would be more appropriate for dynamic activities.

2.13 The role of resistance training in preventing hamstring strain injuries

Resistance training is generally recognised amongst industry professionals to be beneficial to a sportsperson for both injury prevention and sports enhancement (Askling *et al.,* 2003). This has led to strength training being advocated as a preventative measure in order to avoid hamstrings muscle injuries (Stanton and Purdam, 1989). This recommendation is based around evidence from experiments on animal muscles, which have revealed that a stronger muscle can absorb more energy prior to failure than a weaker muscle (Garrett, 1990; 1996). Also there is empirical evidence within humans showing a reduction in the incidences of musculoligamentous injury following the introduction of a progressive programme of resistance training (Askling *et al.,* 2003; Mjølsnes *et al.,* 2004; Brooks *et al.,* 2006).

An eccentric muscle action is described as when the force applied to the muscle exceeds that of which the muscle can produce and hence the muscle is lengthened whilst generating tension (Hortobagyi, 2003). Conventional resistance training consists of performing concentric (muscle shortening) and eccentric (muscle lengthening) actions (Hortobagyi, 2003). Traditional machine weights and free weights exercises combine these actions through agonist and antagonist muscle activation about a joint to perform a movement. A variety of free and machine weights exercises have been recommended for training the hamstrings muscles.

Traditionally the back squat has been proscribed as an exercise to develop the hamstrings (Wright *et al.,* 1999), although recent evidence has shown that the motor unit activation of the hamstrings is greater during stiff leg dead lifts (Wright *et al.,* 1999). In addition, it is well documented that most hamstring strain injuries occur during the late swing phase of the running action (i.e. more extended joint positions) (Stanton and Purdam, 1989). Isear *et al.* (1997) demonstrated that during the squat exercise the EMG activity in the hamstrings was at its greatest in the hold position at the bottom of the squat and at the most flexed knee position during the movement (90 – 60°). These findings suggest the squat is not an appropriate exercise to proscribe an individual to prevent or rehabilitate from a hamstrings injury, as the knee angle where the hamstrings are activated during the movement is not the knee angle where most hamstring injuries appear to occur. Consequently, exercises that engage the hamstrings at the knee angle where hamstring injuries appear to occur (extended knee positions) need to identified. The dead lift is another hamstring exercise, which is often proscribed to individuals with weak hamstrings (Wright *et al.,* 1999). Escamilla *et al.* (2002) demonstrated that the activation of the hamstrings during the dead lift movement was at its greatest at the more extended joint positions (0 - 30° knee angle). These findings suggest that the activation of the hamstring during the dead lift exercise is greatest at the knee angles where most hamstring strain injuries occur. Despite this, the dead lift exercise is a movement that combines both concentric and eccentric actions of the hamstrings (Escamilla *et al.*, 2002). There is increasing amount of evidence pointing towards the advantages of including training optimising eccentric actions to the hamstrings in a strength regime for preventing hamstrings injuries (Proske and Morgan, 2001). It has also been reported that the majority of hamstring strain injuries occur during an eccentric action (Garrett, 1990). In accordance with the principle of training specificity, which denotes that muscle adapts specifically to the mechanical and metabolic stresses to which it is exposed (Baechle, 2000), to induce optimal developments in the eccentric strength of muscle, resistance training methods that emphasis an eccentric action should be utilised. Therefore the dead lift may not be an appropriate exercise to proscribe an individual to prevent or rehabilitate them from a hamstrings strain injury as this exercise combines both concentric and eccentric actions of the hamstrings. Hence, an eccentric based exercise for the hamstrings needs to be identified.

Over the last 10 years interest in eccentric actions and adaptations to this type of training has grown substantially (Brughelli and Cronin, 2007). During eccentric contractions force steeply rises as the muscle is lengthened at increasing velocities; in contrast, during concentric contractions force declines when muscle is shortened at increasing velocities (Hortobagyi, 2003). This can result in over one and a half times the maximal concentric load being moved during eccentric actions (Enoka, 1996). Therefore, in order to stimulate a muscle sufficiently to develop eccentric strength, an eccentric training overload equivalent to at least 120% of a concentric one repetition maximum is recommended (Tan, 1999). Traditionally this type of training requires mechanically loading extra weight in the eccentric phase of the movement, therefore this approach to eccentric training is far more involving (Hortobagyi, 2003) and often requires multiple 'spotters'. Hence, training eccentrically is logistically no easy feat (Hortobagyi, 2003). It has been suggested that by performing the eccentric component of a free weights or machines weights movement at a deliberately slow velocity the exposure of muscle to eccentric overloading is increased and this may serve as a stimulus for developing eccentric muscle strength, although this method is scientifically unproven (Hortobagyi, 2003).

Specialised resistance training machines, initially designed for resistance training in micro-gravity, have recently been utilised in resistance training programmes to induce eccentric overload upon a muscle group (Askling *et al.,* 2003; Tesch *et al.,* 2004; Greenwood *et al.,* 2007; Norrbrand *et al.,* 2008). Such devices are different to conventional gravity dependent training devices (machine and free weights) in that they use the inertia produced by a rotating flywheel to provide resistance to the participant (Berg and Tesch, 1992; Berg and Tesch, 1994). Traditional gravity dependent devices rely on the effect of gravity upon a load to provide resistance to the participant (Norrbrand *et al.,* 2008). The flywheel device works by the force applied during the concentric action upon the lever arm pulling a strap which is attached to the flywheel; in turn this imparts spin to the flywheel against its inertia. Following the concentric action the flywheel will then start to recoil by virtue of its rotary inertia, thus reversing the direction of the movement. It is as the participant resists the recoil of the strap that the muscle performs an eccentric action. The advantage of this type of device over traditional gravity dependent devices is that the more energy that is transferred from the lever arm to the flywheel during the concentric action the faster the flywheel will spin; consequently, when this kinetic energy is transferred to the eccentric phase of the movement greater force will need to be generated to exceed that generated during the concentric action (Norrbrand *et al.,* 2008). Therefore, the flywheel device specifically overloads the muscle in the eccentric part of the movement when compared to the concentric part of the movement. Excellent results in terms of increases in eccentric strength (Tesch *et al.,* 2004; Greenwood *et al.,* 2007), early adaptations in skeletal muscle size (Norrbrand *et al.,* 2008), improved maximal running speed, and reduced incidences of hamstrings strain injuries (Askling *et al.,* 2003) have been reported following the use of this type of flywheel apparatus.

An isokinetic dynamometer is another type of specialist resistance training device in which muscles can be trained eccentrically (Kellis and Baltzopolus, 1995). Like wise excellent results have been reported whilst training upon isokinetic dynamometers, with eccentric training resulting in superior increases in eccentric strength compared to concentric training (Seger *et al.,* 1998; Farthing and Chilibeck 2003) and eccentric training suggested to be the most effect for muscle hypotrophy (Farthing and Chilibeck 2003). Despite these excellent results reported whilst using flywheel devices and isokinetic dynamometers, these training devices are still not readily available, as they are relatively expensive and may not be affordable for most soccer clubs.

An exercise that has received an increasing amount of interest in recent years as a means of training the hamstrings during an eccentric action is the NHE (Brughelli and Cronin, 2007). The main attraction of this exercise over isokinetic and flywheel based machines is that it is a simple partner assisted exercise that requires no additional equipment and can be performed with a squad of players in the "field" (Bahr *et al.,* 2002). The exercise involves the trainee starting in a knelt position with a partner stabilising their legs by securing the ankles. Keeping the hips extended, the aim of the exercise is to lean forward in a smooth motion resisting this forward falling motion with the hamstrings muscles. To achieve maximum loading during this eccentric part of the movement, the hamstrings should be engaged as long as possible until the trainee lands on their hands. The trainee then touches down with their hands and lowers their upper body down until the chest touches the ground. From this position the trainee forcefully pushes off using their hands until they are back in a kneeling position with minimal concentric load on the hamstrings (Bahr and Mæhlum 2004).

To date, the activation of the hamstrings through EMG has been shown to be higher in the NHE when compared to other commonly proscribed field based hamstrings exercises, including the dead lift and back squat exercises (Ebben *et al.,* 2006). Also, the strength increases when incorporating the NHE into a resistance training programme suggests that training with this exercise (eccentrically) compared to training with the hamstrings curl exercise (concentrically) for 10 weeks led to an 11% increase in eccentric strength of the hamstrings (Mjølsnes *et al.*, 2004). These findings suggest that the NHE is the most appropriate field based exercise to date, to prescribe for an individual who is training or rehabilitating their hamstrings to prevent a hamstrings strain injury because the NHE is an eccentric based exercise, the optimal hamstring exercise for motor unit recruitment when compared to other hamstrings exercises (Ebben *et al.,* 2006), and training with the NHE led to improved eccentric strength of the hamstrings (Mjølsnes *et al.*, 2004). Although, to date no research group has investigated the EMG activity of the hamstrings in relation to knee angle during the NHE, and hamstrings strain injuries have been shown to occur at the more extended knee positions (Stanton and Purdam, 1989). An additional advantage of the NHE is that the NHE can be incorporated into warm-up routine time, and since training time is often limited and coaches may be reluctant to redirect time away from technical and tactical training for specific resistance training (Iga *et al.,* In press).

The angle of peak hamstrings torque indicates the working range of motion relative to its length-tension relation of the hamstrings muscles (Proske and Morgan, 2001). Shifting the length tension relationship of the hamstrings to longer lengths has been proposed to improve the hamstrings muscles working range of motion relative to its length-tension relation, conferring protection against initial micro-damage, preventing fibres from reaching a length where they are susceptible to initial damage and a subsequent tear (Proske and Morgan, 2001). Modifications in the length-tension relations of the hamstrings muscles to longer lengths have been indicated after a period of training with the NHE (Brockett *et al.,* 2001; Clark *et al.* 2005). Brockett *et al.* (2001) reported a shift in angle of peak torque production of the hamstrings muscles of 7.7° post exercise. Also a similar shift in the angle of peak torque production of 6.3° in the hamstrings was reported in Brockett *et al.* (2001) study. As a reduced working range of motion of the hamstrings has been proposed as a contributing factor in the aetiology of hamstrings strain injuries (Brockett *et al.,* 2001), based on the findings of Brockett *et al.* (2001) and Clark *et al.* (2005), the NHE would be an appropriate exercise to proscribe an individual with a reduced working range of motion of the hamstrings to increase this range of motion to longer muscle lengths so as to provide protection against initial micro-damage, preventing fibres from reaching a length where they are susceptible to a subsequent tear (Proske and Morgan, 2001).

Brughelli and Cronin, (2007) have criticised the NHE based on the findings of Clark *et al.* (2005) who reported a 30.3% pre and 42.4% post intervention difference in the angle of peak hamstrings torque production between limbs following a 4 week training programme incorporating the NHE. Brughelli and Cronin, (2007) suggested that due to the bilateral nature of the NHE, the stronger limb may compensate for the weaker limb; overtime this may induce or exacerbate existing bilateral strength asymmetries. This implies that resistance training incorporating the NHE may increase bilateral strength asymmetries thereby increasing the susceptibility of the weaker limb to injury (Knapik *et al.,* 1991). The only study to date that has reported eccentric strength of the hamstrings following resistance training with the NHE (Mjølsnes *et al*., 2004) only performed eccentric strength assessments on the right limb and therefore comparisons between limbs and possible imbalances could not be investigated. However, the research to date is conclusive that the inclusion of the NHE in a resistance training programme reduces hamstrings injuries (Mjølsnes *et al*., 2004; Brooks *et al,* 2006). Also, Clark *et al.* (2005) study can be criticised as this investigation employed concentric actions using an isokinetic dynamometer to assess strength changes. These assessments may not have been appropriate to assess changes in eccentric strength following the training programme as the literature indicates that adaptations following eccentric interventions are mode specific (Kellis and Baltzopoulos 1995). However, Clark *et al.* (2005) went on to suggests that, where imbalances between limb in the angle of peak torque productions are present, there may be the need for unilateral eccentric hamstring training to reduce this difference before bilateral eccentric specific training commences. Interestingly, Clark *et al.* (2005) also reported in the same investigation that following 4 weeks training there was a significant increase in vertical jump height (51 – 54.4 cm). This implies that training with the NHE is sports specific as the vertical jump height test is a recognised performance indicator to measure lower body power (Rodacki *et al.,* 2001).

The current research regarding the sports specificity of eccentric training suggests that this type of training is not velocity specific (Kellis and Baltzopoulos 1995). These findings have important implications for proscribing eccentric modes of training for injury prevention for athletes, since most hamstring strain injuries occur to speed athletes (Garrett, 1996) during high speed high intensity situations during the running action (Verrall *et al.,* 2005) when the hamstrings are contracting eccentrically (Stanton and Purdam, 1989). Angular velocities during sporting movements like running can reach in excess of 300°/s (Knapik *et al.,* 1991). The early literature by Ryan *et al.* (1991) reported that eccentric isokinetic training of the hamstrings for 6 weeks at 120°/s lead to a significant improvement in the hamstrings strength of 18.5% and 22.8% at both velocities 60°/s and 120°/s, respectively. Therefore, this author concluded that within the hamstrings muscle group eccentric training was not velocity specific. More interestingly, since this early research which exclusively relied on the effect of eccentric training at one particular angular velocity on the eccentric torque at altering angular velocities, investigations examining the effect of eccentric training at various angular velocities have been conducted (Paddon-Jones *et al.,* 2001; Farthing and Chilibeck, 2003; Shepstone *et al.,* 2005). This research is far more conclusive and suggests that eccentric strength training is not velocity specific and strength training at higher angular velocities leads to a significant improvement in eccentric strength when compared to training at slower angular velocities (Paddon-Jones *et al.,* 2001; Farthing and Chilibeck, 2003; Shepstone *et al.,* 2005). Both Farthing and Chilibeck, (2003) and Shepstone *et al.* (2005) reported that eccentric strength training was not velocity specific when training was performed at either slow or fast angular velocities but the improvement in eccentric strength gains were greater at the faster angular velocities. This suggests that adaptations following eccentric strength training are not velocity specific (Ryan *et al.,* 1991; Paddon-Jones *et al.,* 2001; Farthing and Chilibeck, 2003; Shepstone *et al.,* 2005) and specific eccentric training of the hamstrings is not velocity specific (Ryan *et al.,* 1991). This implies that eccentric resistance training at slower angular velocities (i.e., the NHE) may increase eccentric strength of the hamstrings at faster angular velocities, which is the velocities in running where most hamstrings injuries appear to occur (Verrall *et al.,* 2005).

2.14 Summary of Resistance Training

The NHE has been shown to be the best hamstrings exercise for motor unit recruitment when compared to other hamstrings exercises (Ebben *et al.,* 2006). The neuromuscular adaptations to this eccentric based exercise are improved eccentric strength of the hamstring muscles (Mjølsnes *et al.*, 2004), improved vertical jump height of participants (Clark *et al.* 2005), shift of the optimal angle for eccentric torque to more extended joint positions (Brockett *et al.,* 2001; Clark *et al.*, 2005) which have resulted in a significant reduction in the incidence and severity of hamstrings strain injuries in games players when incorporated into a resistance training programme (Mjølsnes *et al.*, 2004; Brooks *et al.,* 2006). To date, no research group has systematically evaluated the recruitment characteristics of the hamstrings muscle group during the NHE and what effect a four week resistance training programme incorporating this exercise will have on the isokinetic strength characteristics of the hamstrings muscles. Brughelli and Cronin, (2007) have criticised the NHE because the exercise is a bilateral exercise; this author proposed that training with this exercise would exacerbate existing imbalance, although this suggestion has not been investigated through the assessment of eccentric isokinetic strength. Brughelli and Cronin, (2007) also questioned the ability of this exercise to engage and thus train the hamstring muscles at more extended knee angles. However, this postulate also has yet to be examined.

Therefore the aim of this thesis is to investigate, through electromyography analysis, the recruitment characteristics of the hamstrings during the NHE. A second aim is to evaluate, through isokinetic strength assessments, eccentric strength changes and shifts in the length tension relationship in the hamstrings, and if there are asymmetries between limbs following training with the NHE. It also appears that eccentric strength training is not velocity specific (Ryan *et al.,* 1991; Paddon-Jones *et al.,* 2001; Farthing and Chilibeck, 2003; Shepstone *et al.,* 2005), and no research group has investigated if eccentric training incorporating the NHE is velocity specific. Consequently, a third aim is to investigate if eccentric strength training incorporating the NHE is velocity specific.

CHAPTER III

MATERIALS AND METHODS

3.1 Participants

Eighteen male professional football players with no history of musculoligamentous injury about the knee and no experience of systematic eccentric-based resistance training of the hamstrings muscles were recruited for this study. The number of participants was calculated based on statistical power calculations (Vincent, 1995) of the hamstrings eccentric peak torque production and the angle of peak torque production at each test velocity (60, 120, 240°/s) in the DOM limb, a range of participants per group were indicated (see appendix A) to distinguish the minimum clinically important difference from the statistical null. All players had between 2-8 years experience of professional soccer training. The players engaged in 4 training sessions per week for a total of 12 to 16 hrs and played one or two competitive matches a week; the players' training was designed to improve technical and tactical skills and develop aspects of game related fitness. Participants were randomly assigned either as the training group (10 players) or a non-training group (8 players). The players in the training group performed 4 weeks of training incorporating the NHE (see section 3.2); the non-training group continued with their normal training methods. Mean age, stature, body mass, and details of body composition for each group are displayed in Table 3.1. The University's Research Ethics committee approved all procedures, and after being fully informed of their involvement (see appendix B) signed consent (see appendix C) and health questionnaires (see appendix D) were obtained from each participant prior to commencement of the study. All participants were informed that they had the right to withdraw from the study at any time without prejudice to access of services, which were already being provided or may subsequently be provided to the participant.

Table 3.1: Participants anthropometric characteristics.

	Control Group	Training Group
Age (year)	22.3 ± 3.9	23.4 ± 3.3
Stature (m)	1.85 ± 9.7	1.77 ± 6.8
Body mass (kg)	78.0 ± 11.1	78.0 ± 8.2
Sum of 4 skinfolds (mm) *	27.8 ± 4.8	26.5 ± 7.0

* Sum of four skinfold measurements at the triceps, biceps, suprailliac and subscapular

3.2 Training intervention

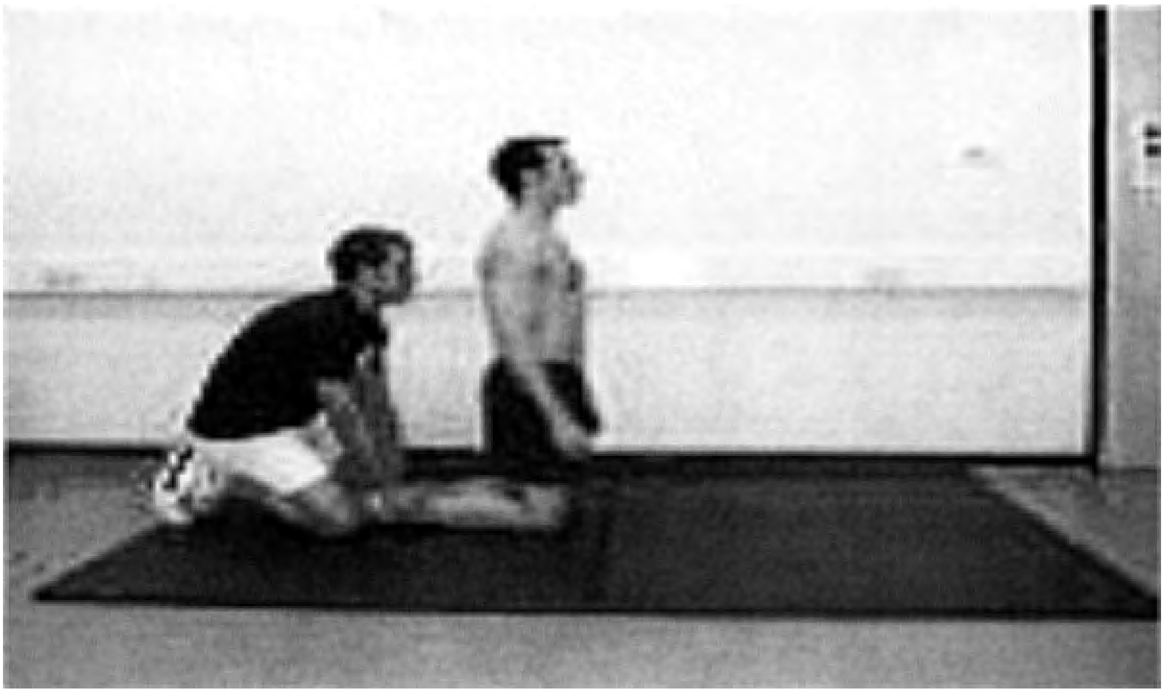
The training group followed a previously applied resistance training programme incorporating the NHE (Mjølsnes *et al.,* 2004). The volume of training is illustrated in Table 3.2. The training group performed the NHE as part of their daily warm-up routine. In the NHE, the trainees started in a knelt position with a partner securing the legs by holding the ankles. The movement was to lean forward at the knees whilst maintaining the hip joint in an extended position. Participants were advised to resist the falling motion for as long as possible by engaging the hamstrings muscles. If this was not possible they had to try and maintain the tension in their hamstrings even after they had fallen. Participants were asked to use their hands to both brake their fall and return their torso to the starting position, therefore minimising the concentric contraction of the hamstrings during the movement. The control group continued their normal warm-up routine.

Table 3.2: Four week NHE training programme.

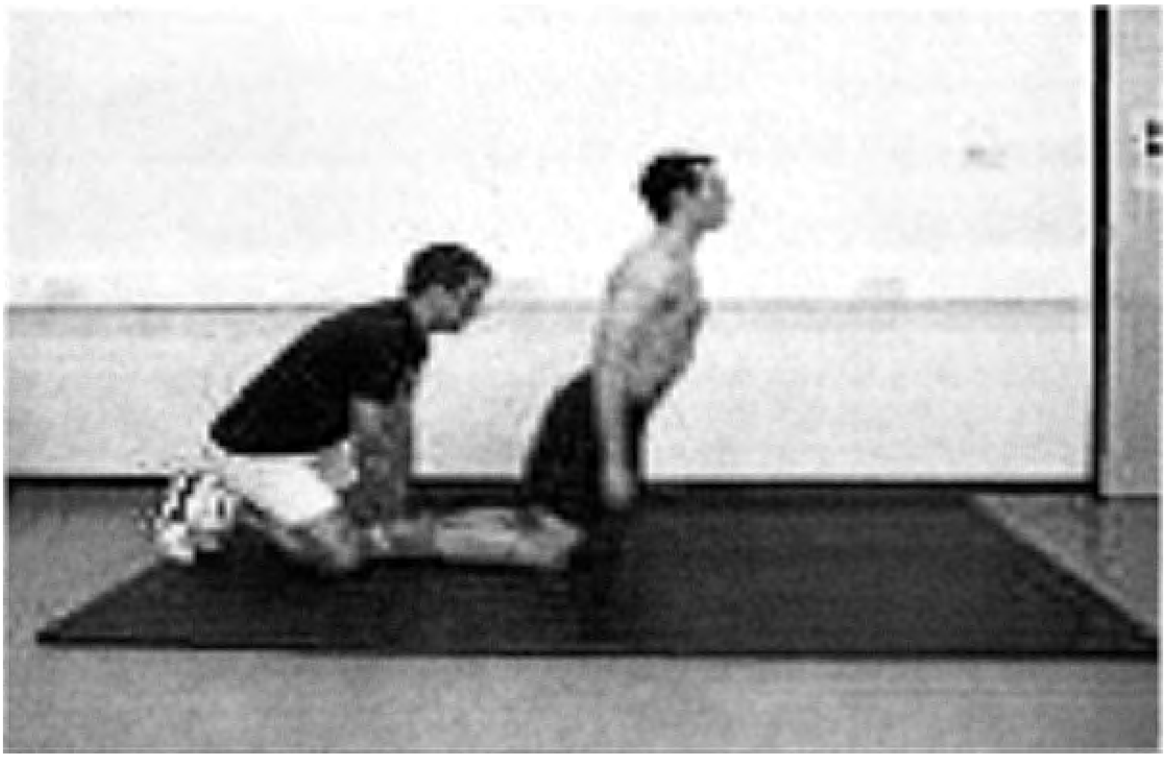
Week	Session per week	Sets and Reps
1	1	2/5
2	2	2/6
3	3	3/6
4	3	3/8

3.3 The Nordic Hamstring Exercise

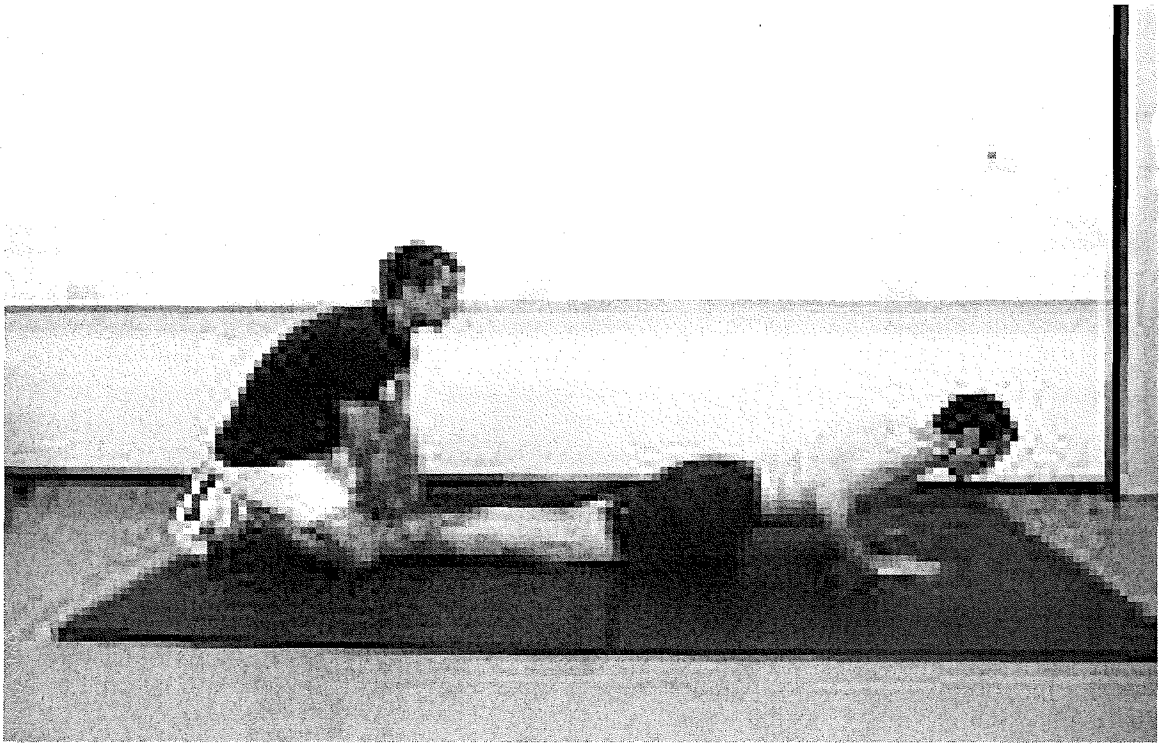
Start position (start of phase 1)



Start of phase 2 (roughly)



End position (end of phase 3)



3.4 Isokinetic eccentric assessments

Isokinetic eccentric assessments of the hamstrings were performed on a Biodex isokinetic dynamometer (System-3, Biodex Corp., Shirley, NY, USA). Participants were familiarised with the dynamometer and the testing protocols one week prior to formal assessment. Peak torque was assessed in both limbs at 60, 120 and 240°/s. Limb dominance was determined through interview and was defined as the preferred leg when kicking a football. Formal assessments were commenced with a standardised warm up consisting of 3 minutes of cycling at 50 W on a cycle ergometer (Excalibur Sport, Lode, The Netherlands). Isokinetic assessments were performed from a prone position with the hips extended during unidirectional movements in which following the eccentric action, the participants' limb was passively returned to the starting position by the dynamometers' lever-arm. A strap designed to stabilise the trunk was applied across the waist, and participants were instructed to place their arms to the side of the reclined chair and hold the straps provided. This provided constant conditions across all participants and aimed to mitigate additional movements which may have confounded the test results. The axis of rotation of the dynamometer was visually aligned with the lateral femoral condyle of the knee with the knee flexed at approximately 90°. The resistance pad was placed proximal to the medial malleolus, allowing full dorsi-flexion and plantar-flexion of the ankle joint. Motion ranged from 90° to 10° of knee extension (0° representing full extension). Slow angular velocity assessments were performed before assessment at the higher angular velocities as this may facilitate learning during assessments at high angular velocity of the knee and reduce the risk of injury (Gaul, 1996). At each angular velocity two sub-maximal warm-ups were followed by four maximal test efforts. Limbs were tested in a randomised order across participants but standardised across trials. Five seconds of rest were allowed between each maximal effort. Standardised verbal encouragement was given before each maximal effort, and visual feedback of the recorded torque was provided. Participants were given a rest of 60 s between movements at different angular velocities. The gravitational moment of the leg-foot segment was determined from anthropometric data expressing the weight of the segment relative to the total body weight of the participant and the position of the centre of mass (Kellis and Baltzopoulos, 1996). From this data and the length of the segment (lateral femoral epicondyle-malleolus) moments at 0° of knee extension were calculated (Kellis and Baltzopoulos, 1996). The gravitational moment at any angle during the range of motion was obtained as the product of the above moment and the cosine function of the angle (Kellis and Baltzopoulos, 1996). To avoid the effects of acceleration and deceleration of the lever arm on torque output, only peak torque data obtained from the period of constant velocity, within a 5% range of the preset angular velocity, were analysed (Iga *et al.,* In press).

3.5 Electromyography

The recruitment characteristics of the hamstrings muscles when performing the NHE were examined by the use of surface EMG. For maximum signal detection each bipolar surface electrode (DE– 2.3 MA; DelSys Inc., Boston, MA, USA) was positioned on the belly of the muscle perpendicular to the muscle fibres. Electrodes were placed on the medial hamstrings (MED) and lateral hamstrings (LAT) represented by the semitendinosus and semimembranosus muscles and the biceps femoris long head and biceps femoris short head respectively, in both the dominant (DOM) and non-dominant (NDOM) limbs. Following the application of surface electrodes participants were instructed to perform five 'Nordic' Hamstring Curls. Five repetitions were selected to obtain EMG data representative of the muscle activity during the exercise without extensive fatigue to the muscles involved. Electromyography was quantified with an 8-channel DelSys EMG telemetry system (DelSys Myomonitor III, DelSys Inc., Boston, MA, USA). Raw EMG data was collected at a sampling frequency of 1024Hz and sent directly to the DelSys Acquisition software package set up on a Toshiba Laptop (L20, Toshiba Corp. Tokyo, Japan). The unit included a common mode rejection ratio of >80 dB and an amplifier gain of 1000. Raw EMG data was band pass filtered at 20 – 450 Hz using the DelSys Acquisition software.

An electrogoniometer (S700; DelSys Inc., Boston, MA, USA) was applied to each participant's right knee, with the axis of rotation centred over the lateral femoral condyle, with the knee flexed at approximately 90°. The proximal arm of the electrogoniometer was placed on the lateral thigh and aligned with the lateral midline of the femur using the greater trochanter as a reference point. The distal arm was placed on the lateral aspect of the shank and aligned with the lateral midline of the fibula with the lateral malleolus as a reference point. The electrogoniometer allowed the exploration of the interaction between the EMG activity of the muscles of the hamstrings during phase 1 (1st 1/3 of the movement), phase 2 (2nd 1/3 of the movement), and phase 3 (3rd 1/3 of the movement) during the range of motion of the NHE. The electrogoniometer signal was included within the same 8-channel DelSys EMG telemetry system as the EMG signal and therefore the sampling frequency was set at 1024Hz. The velocity of the NHE was standardised by the use of a metronome. The metronome was set to one beat per second and the participants were instructed to perform the eccentric part of the NHE in three seconds. Participants were familiarised with this velocity by watching other subjects perform the NHE.

The start of the NHE was standardised through the construction of 95% confidence limits around the first 250 electrogoniometer data points. This represented a 0.25s epoch which was considered sufficient to represent a stationary start position for the participant. When two consecutive electrogoniometer data points dropped below the 95% confidence limit the movement was considered to have started. The finish of the 'Nordic' Hamstring Curl was calculated to be when the electrogoniometer data points reached its lowest point in the movement for two consecutive data points.

Raw EMG data was converted to RMS data within the DelSys Data Analysis software package. The EMG RMS data for each section of the movement was normalised against the maximum EMG RMS amplitude recorded in the same muscle over a 2 ms window during the 5 repetitions of the NHE. The mean RMS value from the five repetitions of the NHE during each section of the movement was used to represent the EMG activity of that muscle group during that section of the movement.

The reliability characteristics associated with the peak torque data and the angle of peak torque data were investigated prior to the commencement of the main study through the use of 95% limits of agreement (LOA). Data was collected through a test retest scenario using the same isokinetic procedures highlighted in methods 3.4. Eighteen males (mean, SD; age, 23.0 ± 5.9 yrs; height, 181.5 ± 10.3 cm; body mass, 78.2 ± 9.0 kg) with no history of musculoligamentous injury about the knee and no experience of systematic eccentric-based resistance training of the hamstrings muscles were recruited for this study. The University's Research Ethics committee approved all procedures, and after being fully informed of their involvement signed consent and health questionnaires were obtained from each participant prior to commencement of the study. All participants were informed that they had the right to withdraw from the study at any time without prejudice to access of services, which were already being provided or may subsequently be provided to the participant. Bland-Altman plots for the data are presented in appendix E. The results are displayed in tables 3.3 and 3.4. The 95% LOA associated with each test velocity (60°/s, 120°/s, 240°/s) in both the DOM and NDOM limbs for both peak torque production and angle of peak torque production can be considered relatively wide as the magnitude of change would have to be high to report a difference.

Table 3.3. 95% Limits of Agreement for hamstrings peak torque

Velocity; Limb	Bias ± 95% LOA
60°/s; DOM limb	-3 Nm ± 23 Nm
60°/s; NDOM limb	-3 Nm ± 26 Nm
120°/s; DOM limb	0 Nm ± 18 Nm
120°/s; NDOM limb	-1 Nm ± 27 Nm
240°/s; DOM limb	1 Nm ± 35 Nm
240°/s; NDOM limb	1 Nm ± 24 Nm

Table 3.4. 95% Limits of Agreement for hamstrings angle of peak torque

Velocity; Limb	Bias ± 95% LOA
60°/s; DOM limb	11° ± 38°
60°/s; NDOM limb	0° ± 43°
120°/s; DOM limb	-2° ± 41°
120°/s; NDOM limb	3° ± 36°
240°/s; DOM limb	1° ± 10°
240°/s; NDOM limb	0° ± 7°

3.5 Data analysis

Statistical analysis was performed using SPSS version 14 software package (Chicago, Ill). The level of significance was set at $P \leq 0.05$ for all tests. To examine the difference in muscle EMG activity during the NHE between the DOM and NDOM limbs (LAT and MED pooled), a paired sample *t*-test was applied. Where differences were not present, further analysis of the DOM limb through a two-way (2x3) fully repeated measures ANOVA was applied to examine the interaction effect of muscle region (LAT/MED) and knee position (phase 1, phase 2, phase 3) on EMG muscle activity during the NHE. Significant interaction effects and main effects were further examined using Bonferroni-corrected post hoc *t*-tests.

To examine the effect of the NHE training programme on the DOM and NDOM isokinetic peak torque production and angle of peak torque production at each test velocity, two-way (2 x 2) between (group) within (time) factorial analysis of variance design was applied. When a main effect for time was reported, the interaction between time and limb for isokinetic peak torque for each velocity was analysed using two-way (2 x 2) fully repeated measures analysis of variance. Significant main effects were further examined using Bonferroni-corrected post hoc *t*-tests.

CHAPTER IV

RESULTS

4.1 Electromyographic analysis of the NHE

No difference in the EMG normalised RMS amplitude of the hamstrings between the limbs ($t_{37} = 0.137$; $P = 0.413$) was observed. Two-way fully repeated measures ANOVA demonstrated the absence of an interaction between muscle region and joint angle for the normalised RMS amplitude of the hamstrings in the DOM limb ($F_{2,35} = 1.775$, $P = 0.184$). Although no main effect for muscle region was observed ($F_{1,36} = 1.605$, $P = 0.213$), main effects for angle on RMS amplitude were demonstrated ($F_{2,35} = 154.354$, $P < 0.001$). Bonferroni corrected post-hoc t-tests indicated that in both muscle regions in the DOM limb the RMS amplitude was significantly higher at the more extended knee positions (see figure 4.1).

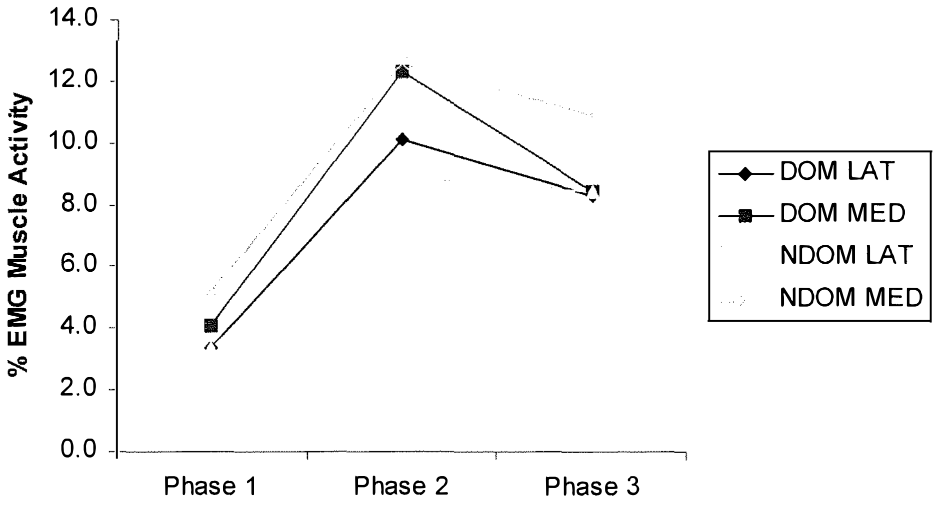


Figure 4.1. Electromyographic activity of the hamstrings muscle during the 'Nordic' hamstring exercise prior to training.

4.2 Isokinetic peak torque in the training study

Significant interaction effects for time by group were observed for eccentric strength assessments of the DOM and NDOM limbs across all assessment velocities (60°/s; DOM, $F_{1,16} = 5.11$, $P = 0.04$; NDOM, $F_{1,16} = 6.84$, $P = 0.02$; 120°/s; DOM, $F_{1,16} = 4.46$, $P = 0.05$; 240°/s; DOM, $F_{1,16} = 8.10$, $P = 0.01$; NDOM, $F_{1,16} = 5.68$, $P = 0.03$). Main effects for time for the DOM limb were observed for the slowest velocity (DOM 60°/s, $F_{1,16} = 5.58$, $P = 0.03$) but not for the fastest velocities (DOM 120°/s, $F_{1,16} = 2.73$, $P = 0.12$; DOM 240°/s, $F_{1,16} = 1.24$, $P = 0.28$). Main effects for time were observed for the NDOM limb across all velocities (NDOM 60°/s, $F_{1,16} = 10.96$, $P < 0.001$; NDOM 120°/s, $F_{1,16} = 6.75$, $P = 0.02$; NDOM 240°/s, $F_{1,16} = 12.24$, $P < 0.001$). Eccentric peak torque production in the training group improved 8 to 21%, whereas no significant change over time was observed for the non training group (~4%) (see table 4.1)

Table 4.1. Isokinetic peak torque strength (Nm) of the hamstrings muscles in the training and control group pre and post the training intervention (Mean ± SD).

Velocity (°/s)	Training				Controls			
	Pre		Post		Pre		Post	
	DOM	NON NOM	DOM	NON DOM	DOM	NON DOM	DOM	NON DOM
60	115 ± 42	99±30	132±43* **	119±37* **	120±38	107±37	121±33	109±29
120	121±45	105±32	134±42*	119±33 **	122±40	105±37	121±35	110±28
240	121±43	102±34	130±42*	122±32* **	114±46	103±34	110±41	107±27

Note; * Indicates the significant interaction effects for time by group. ** Indicates the significant main effects for time.

Further analysis of the training group indicated no interaction effects for time by limb across velocities (60°/s, $F_{1,18} = 0.20$, $P = 0.66$; 120°/s, $F_{1,18} = 0.026$ $P = 0.88$; 240°/s, $F_{1,18} = 2.48$, $P = 0.13$). Main effects for time across all velocities were observed ($F_{1,18} = 23.65$, $P < 0.001$) although no main effects for limb across all velocities were observed (F

$_{1,18} = 0.75$, $P = 0.40$). The improvements in leg strength when the DOM and NDOM were pooled together were not velocity specific (see figure 4.2).

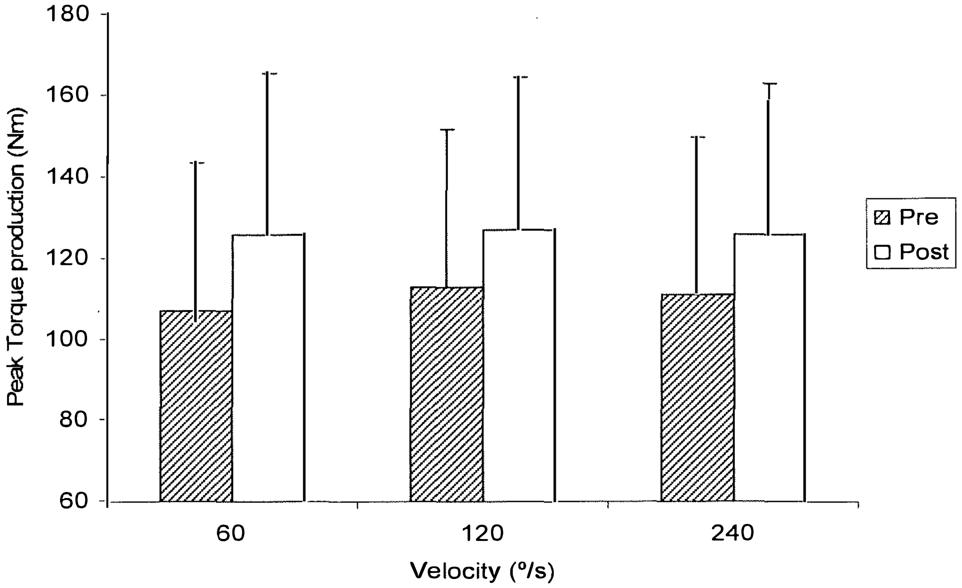


Figure 4.2. Isokinetic hamstrings strength of the 'Nordic' hamstring exercise training group in the DOM and NDOM limbs (data pooled) pre and post the training intervention across test velocities.

4.3 Isokinetic angle of peak torque production in the training study

Non-significant interaction effects for time by group were observed for angle of peak torque production in all test conditions ($F_{1,16} = 0.99$, $P = 0.44$). No main effects for time ($F_{1,16} = 1.85$, $P = 0.33$) or group ($F_{1,16} = 0.59$, $P = 0.61$) were identified (see table 4.2).

Table 4.2. Isokinetic angle of peak torque production (°) of the hamstrings muscles in the training and the control group pre and post the training intervention (Mean ± SD)

Velocity (°/s)	Training				Controls			
	Pre		Post		Pre		Post	
	DOM	NON DOM	DOM	NON DOM	DOM	NON DOM	DOM	NON DOM
60	34±19	34±16	31±18	26±12	30±19	27±16	25±11	25±14
120	31±21	30±17	22±14	23±14	27±17	26±13	23±16	27±15
240	28±4	29±5	25±3	28±5	28±5	29±9	29±4	29±4

CHAPTER V

DISCUSSION

5.1 Main findings

This investigation is the first of its kind to compare the hamstrings involvement during the NHE. The primary finding from the EMG data in this study is that the NHE involves the hamstrings to a greater degree at the more extended knee angles during the movement (phase 2 and phase 3) when compared to the initial stage of the movement (phase 1). There seems to be no difference between the amount of involvement of the DOM and NDOM limbs during the exercise and there appears to be no difference between the contribution of the LAT and MED hamstrings during the movement.

When the normalised RMS EMG data during the NHE between limbs is compared (i.e., the LAT and MED normalised RMS data are pooled), the data indicates that the DOM and NDOM limbs contribute to the exercise similarly, with 7.8% (DOM) and 8.3% (NDOM) of the peak RMS EMG value produced by the respective muscle groups during the complete movement. It has been supposed that because the NHE is a bilateral exercise for the hamstrings muscle group (i.e., the DOM and NDOM limb are activated during the movement) that the DOM limbs involvement during the movement may be greater to compensate for the potentially weaker NDOM limb (Brughelli and Cronin, 2007); according to this theory, over time, it may be supposed that training with this exercise may lead to or exacerbate any existing bilateral strength asymmetries. An imbalance in strength between the DOM and NDOM limbs has been associated with an increase in reported injuries to the weaker limb (Knapik *et al.,* 1991). Despite this supposition by Brughelli and Cronin (2007) there is amounting evidence that training with the NHE reduces the amount of hamstrings injuries (Mjølsnes *et al.*, 2004; Brooks *et al.,* 2006). Furthermore, the EMG data from the present investigation suggests there is no difference in the amount of involvement of the DOM or NDOM limbs during the NHE, implying that Brughelli and Cronin, (2007) supposition is incorrect, and the NHE will not increase existing bilateral strength asymmetries. The implications of the findings from this investigation are supported by Mjølsnes *et al.* (2004) and Brooks *et al.* (2006) who reported reduced incidence of hamstrings injuries after a resistance training programme of the NHE. It is recognised that when comparing the EMG data across limbs in the present study, the EMG data was normalised against the maximum EMG RMS amplitude recorded in the same muscle during the 5 repetitions of the NHE. Therefore, the comparison in the present study between EMG data across limbs is relative and not absolute.

Further analysis of the EMG data in the DOM limb demonstrated that the LAT and MED hamstring muscles during the three phases of the NHE produced a similar amount of EMG activity. When the RMS EMG data produced by the LAT and MED hamstrings were analysed during the complete movement, the LAT and MED involvement were 7.3% (LAT) and 8.2% (MED) respectively of the peak RMS EMG value produced by that muscle group during the movement. However, it has been demonstrated that the ratio of LAT and MED hamstring muscle activation can be altered with changes in the foot rotation position (Lynn and Costigan, 2008). Lynn and Costigan (2008) revealed that through internal foot rotation the MED to LAT hamstring ratio could be increased and external foot rotation decreases this ratio. Based on the normalised RMS EMG data from this present study, the LAT and MED muscles involvement during the NHE were similar. Despite this apparent similarity, the present investigation did not attempt to standardise the internal external rotation of the participants' feet and therefore alterations in the LAT and MED hamstrings involvement due to foot rotation during the NHE could not be systematically investigated. This limitation is recognised, and a study aimed to standardise foot position could investigate if an alteration in foot position leads to a greater activation of either MED or LAT hamstring during the NHE, as an increase in activation of either the MED or LAT hamstring could create muscle imbalances, which could increase susceptibility to injury.

In the DOM limb, both the LAT and MED hamstrings muscles' normalised RMS EMG data showed a higher involvement in the movement at the more extended knee positions. The normalised RMS EMG in phase 2 and 3 of the movement was 11.2% (phase 2) and 8.3% (phase 3) of the peak RMS EMG data produced by that muscle respectively during the movement, compared to 3.7% in phase 1 of the movement. A proposed limitation for the NHE is that as subjects lower their body, gravity becomes a factor and they are unable to support their own body weight at around 30° of knee extension (Brughelli and Cronin, 2007). Studies have shown that around 30° and beyond of knee extension is the angle at which the hamstrings produce peak torque when assessed using isokinetic dynamometry (Brockett *et al.,* 2001; Clark *et al.,* 2005). Although participants appeared not to be able to lower their body weight in a controlled manor to 30° of knee extension, based on the results of the present study, the involvement of both the LAT and MED hamstrings muscles are still significantly higher in this section of the movement when compared to the initial part of the movement. One explanation for this increase in EMG activity in the hamstring muscles at the more extended joint positions could be that the hamstrings are co-contracted during knee extension movements so as to stabilise the knee joint (Hirokawa *et al.,* 1991). As the participants are no longer able to fully engage their hamstrings at the more extended knee positions during the movement this serves to increase the movement velocity at this stage of the movement. This suggests that the increases in EMG at the more extended knee positions could be in response to the need to increase the stability of the knee so as to compensate for this increase in movement velocity (Hirokawa *et al.,* 1991). A second explanation for this increase in EMG activity in the hamstrings muscles at the more extended joint positions could be simply that gravitational effects are greater at the more extended knee positions during the movement and subsequently even after a loss of control in the movement the hamstrings muscles activation is increased to compensate for the increase effects of gravity at these more extended knee positions. As the participants in the current study were not able to fully engage the hamstrings through the full range of motion in the NHE, until an investigation is designed to compare the muscle recruitment patterns of the hamstrings during the NHE between participants that can engage their hamstrings through the full range of motion and participants that can't, these are just speculations based on current research in the area.

The dead lift is a hamstring exercise that is often proscribed to individuals with weak hamstrings (Wright *et al.,* 1999). Escamilla *et al.* (2002) demonstrated that the activation of the hamstrings during the dead lift movement was at its greatest at the more extended joint positions (0 - 30° knee angle). This suggests that the activation of the hamstring during the dead lift exercise is greatest at the knee angles where most hamstrings strain injuries occur. The EMG data from the current study also demonstrates that the activation of the hamstrings during the NHE is at its greatest during the more extended knee joint positions. In addition, the activation of the hamstrings has been shown to be higher in the NHE when compared to the dead lift exercise (Ebben *et al.,* 2006); also the dead lift exercise is a movement which combines both concentric and eccentric actions of the hamstrings (Escamilla *et al*., 2002). It has been reported that the majority of hamstrings strain injuries occur during an eccentric action (Garrett 1990) and to induce optimal developments in the eccentric strength of muscle, resistance training methods that emphasise an eccentric action should be utilised (Baechle, 2000). This suggests that the NHE is a more appropriate exercise than the dead lift to prescribe for an individual who is training or rehabilitating their hamstrings to prevent a hamstring strain injury, not only because the NHE engages the hamstrings muscles at the knee angle where hamstrings injuries appear to occur but the NHE is an eccentric based exercise that has been shown through the use of EMG to engage the hamstrings to a greater degree than the dead lift exercise (Ebben *et al.,* 2006).

The effect of a four week training programme incorporating the NHE on the isokinetic eccentric strength of the hamstrings muscle group was also investigated. The primary findings from the isokinetic strength assessments were that a four week training programme incorporating the NHE does lead to an increase in the eccentric strength of the hamstrings across angular velocities in both the DOM and NDOM limbs. The isokinetic eccentric strength assessments also indicated the improvements in peak torque following the training programme were symmetrical across both the DOM and NDOM limbs, and appear not to be specific to the velocity of training. However, surprisingly, the angle of eccentric peak torque production was unchanged following the training intervention; this observation is in contrast to the current published literature that suggests after eccentric training the angle of peak torque production is reduced to longer muscle lengths (Brockett *et al.*, 2001; Clark *et al.,* 2005). This contrast could possibly be explained by the differences in test conditions used in the present study (prone isokinetic testing) compared to the seated position used in the studies which have reported a shift in the angle of peak torque production to longer muscle lengths. The non-significant statistical results may be explained by the high variability associated with these measurements (Table 3.4). Also, based on the statistical power calculations for sample size, depending on the velocity at which the test is performed at, between 471 and 17 participants would be required to distinguish the minimum clinically important difference from the statistical null.

The results from the present study indicate that the training group increased their eccentric isokinetic peak torque production by between 8 – 21% across limbs at the different angular velocities (table 4.1). These results are similar to other studies that have incorporated eccentric strength training of the hamstrings into a training programme of professional soccer players. Askling *et al.* (2003) trained the hamstrings of professional soccer players for ten weeks on a YoYo flywheel ergometer (Non gravity dependent device) and reported a 19% increase in isokinetic eccentric peak torque production in the hamstrings. Likewise, Mjølsnes *et al.* (2004) trained the hamstrings of professional soccer players for ten weeks with the NHE; this author reported an 11% increase in isokinetic eccentric peak torque production in the DOM hamstring following the training programme. However the results from the current study do contradict the results reported by Clark *et al.* (2005) who reported a minor change in the peak torque production in the hamstrings of only 2% from 99 to 101Nm following training. Clark *et al.* (2005) incorporated exactly the same four week NHE training programme as used in the current study. However, Clark *et al.* (2005) did employ concentric isokinetic strength assessments following the four week training programme and the present study employed eccentric isokinetic strength assessments. The literature indicates that eccentric training is generally mode specific, and that eccentric isokinetic assessments of strength are more appropriate than concentric isokinetic assessments to assess changes in eccentric strength following eccentric training (Kellis and Baltzopoulos 1995; Higbie *et al.,* 1996; Seger *et al.,* 1998). Therefore, the concentric isokinetic strength assessment used in Clark *et al.* (2005) investigation following the four week eccentric training programme may not have been appropriate to assess the likely changes in the eccentric strength of the hamstrings. The isokinetic strength assessments performed in the current study, and those of Askling *et al.* (2003) and Mjølsnes *et al.* (2004) (i.e. eccentric action) were more appropriate to assess strength changes following an eccentric training programme, as they were mode specific. Hence, the strength gains reported in Askling *et al.* (2003) and Mjølsnes *et al.* (2004) and this present study are more representative of the eccentric strength changes that occurred in the hamstrings muscle group following an eccentric training programme.

The duration of the eccentric training programme utilized in the current study was four weeks. Both Askling *et al.* (2003) and Mjølsnes *et al.* (2004) studies investigated the effect of a ten week eccentric training programme on the strength of the hamstrings. Despite the short period of training used in the present study the increase in eccentric peak torque production of 15% (when DOM and NDOM and test velocities are pooled) was similar to that observed in Askling *et al.* (2003) (19%) and Mjølsnes *et al.* (2004) (11%) studies. This rapid improvement in the eccentric strength of the hamstrings could possibly be explained by the findings of Iga *et al.* (In press) who reported that soccer training and games play may asymmetrically develop the strength of the knee joint muscles in favour of quadriceps dominance. This increase in quadriceps strength would create an imbalance between the quadriceps and hamstring, affectively leading to a deconditioning affect upon the hamstrings muscles when compared to the quadriceps muscles. Therefore, stimulating the hamstrings through strength training will lead to a rapid change in hamstring strength so as to correct for imbalance in strength between the hamstrings and quadriceps. In addition, the increase in eccentric strength observed in Askling *et al.* (2003) and Mjølsnes *et al.* (2004) studies may have occurred in the early part of the training programme (first four weeks), and the subsequent 6 weeks of training served to increase slightly, or even only maintain the eccentric strength of the hamstring, rather than enhance it. It is well documented in the literature that the increases in strength that are observed in the early part of a training programme can be attributed to neural adaptations (Sale, 1998; Gabriel *et al.*, 2006). As the training period in the current study was limited to only 4 weeks, and eccentric strength was not assessed during stages of the training programme, it is recognised that this suggestion is only speculative without a further study designed to assess isokinetic eccentric strength during stages of a longer training programme incorporating the NHE.

The increase in isokinetic eccentric peak torque illustrated by the current study within the NHE training group were symmetrical in both the DOM and NDOM limbs across all test angular velocities, illustrated by no differences in interaction effects for time by limb and no main effects for limb across all velocities. Following the training programme the increase in isokinetic eccentric peak torque in the DOM and NDOM limbs was 15% and 20% respectively at 60°/s, 11% and 13% respectively at 120°/s and, 8% and 19% respectively at 240°/s (table 4.1). As previously discussed it has been suggested that because the NHE is a bilateral movement for the hamstrings muscle group that possibly the DOM limb's involvement during the movement will be greater to compensate for the weaker NDOM limb (Brughelli and Cronin, 2007). This postulate suggests that training with the NHE will lead to a greater increase in the isokinetic eccentric peak torque in the DOM limb compared to the NDOM limb which may cause or lead to increases in existing bilateral strength asymmetries. Bilateral strength asymmetries have been associated with hamstring strain injuries (Knapik *et al.,* 1991). However, the results from this study suggest that this postulate is false and that findings, based on isokinetic eccentric assessment the hamstrings of the DOM and NDOM limb's, show a similar increase in both limb's for isokinetic eccentric torque production following training with the NHE. This suggests that the NHE is an appropriate exercise to prescribe for an individual for training the hamstrings eccentrically.

In agreement with the current literature (Kellis and Baltzopoulos 1995; Higbie *et al.,* 1996; Seger *et al.,* 1998) the isokinetic strength assessments from the current study indicated that the gains in eccentric strength following the four week training programme with the NHE were not velocity specific (figure 4.2). As the participants were asked to perform the NHE at an angular velocity of 30°/s (90° in 3 secs) based on the literature (Kellis and Baltzopoulos 1995; Higbie *et al.,* 1996; Seger *et al.,* 1998) the increase in eccentric strength in both the DOM and NDOM limbs across the three angular velocities tested

(60°/s, 120°/s, 240°/s) would indicate that the increases in strength were not velocity specific. It is recognised that within the current study the percentage increase in eccentric strength in the DOM limb at the higher angular velocities (11% and 8%) was less than that in the NDOM limb (13% and 19%). Despite this, there were still increases in eccentric strength reported at these angular velocities (120°/s, 240°/s) in both the DOM and NDOM limbs despite the angular velocity (30°/s) in the training programme being significantly slower. This implies that training using the NHE at slower angular velocities could provide protection against injuries that occur during running and sprinting activities where angular velocity can be in excess of 300°/s (Knapik *et al.,* 1991). Interestingly, recent research suggests that despite eccentric training not being velocity specific, improvements in eccentric strength are greater when training is performed at faster angular velocities (Farthing and Chilibeck, 2003; Shepstone *et al.* 2005). The angular velocity that the NHE was performed at in this study would be considered slow if performed upon an isokinetic dynamometer. If through training with the NHE participants can perform the NHE to full range (to the floor) and improvements in eccentric strength gains are greater at training modalities at higher angular velocities (Farthing and Chilibeck, 2003; Shepstone *et al.,* 2005), increasing the angular velocity of the movement through a partner could serve to increase eccentric strength of the hamstrings even further. Alternatively, perhaps performing the NHE at faster angular velocities may reduce the exposure of the muscle to eccentric overload, therefore reducing the strength improvements reported in the current study. These discussions are beyond the scope of the present study and therefore a study designed with the aim to investigate the eccentric strength changes following fast and slow performance of the NHE is recommended.

The results of the present study conflict with the recent research (Brockett *et al*., 2001; Clark *et al.,* 2005) into alterations in the length tension relationship of the hamstrings muscle group following a training programme of eccentric exercise. The present study indicated that there were no interaction effects for time by group for angle of peak torque production in all test conditions. Also, no main effects for time and group were reported. These results suggest there were no alterations in the length tension relationship for the hamstrings in the training group following the training intervention in both the DOM and NDOM limbs across all test velocities (see table 4.2). However, Brockett *et al.* (2001) reported a shift in peak torque production for the hamstrings to longer muscle lengths following a single bout of eccentric exercise with the NHE. After this single bout the angle of peak torque production shifted 7.7°; this shift was still present 10 days after the exercise bout. Clark *et al.* (2005) implemented exactly the same NHE training programme used in the current study to a similar sample group (Australian Rules football players) and reported that there was a 6.3° shift in the angle of peak torque production for the hamstrings to longer muscle lengths following the four week training programme. It is postulated that in the hamstrings the initial damage which may manifest into a more serious injury later in a session occurs beyond the optimal length, on the descending limb of the muscle's length-tension relation (Brockett *et al.,* 2004). Consequently, shifting the angle of peak torque production to longer muscle lengths will reduce the amount of hamstrings action that is on the descending limb of the length tension relationship thereby reducing this muscles' susceptibility to a strain injury. A possible explanation for this difference between the findings from the isokinetic strength assessments in the present study and both Brockett *et al.* (2001) and Clark *et al.* (2005) studies could be the differences in the isokinetic strength assessments employed between studies.

Firstly, it is important to note, within the present study isokinetic strength assessments were performed during an eccentric action, but in the studies of both Brockett *et al.* (2001) and Clark *et al.* (2005) strength assessments were performed during a concentric action of the hamstrings. The literature implies that isokinetic eccentric actions are generally mode specific (Kellis and Baltzopoulos 1995), and that eccentric isokinetic assessments are more appropriate than concentric isokinetic assessments to assess changes in muscle adaptations following eccentric training (Higbie *et al.,* 1996; Seger *et al.,* 1998). Therefore, it can be argued that the strength assessments employed in the present study which did not report shifts in the angle of peak torque production may have been more appropriate than the strength assessments employed in Brockett *et al.* (2001) and Clark *et al.* (2005) studies which did report shifts in the angle of peak torque production. However, it is recognised there may be limitations to the strength assessments used in the present study which may also explain the discrepancies between results. In both Brockett *et al.* (2001) and Clark *et al.* (2005) studies the isokinetic strength assessments were performed in a seated position, in the present study isokinetic strength assessments were performed in a prone position. Based on the results of this present study, there appears to be a high random error associated with eccentric isokinetic strength assessments performed in the prone position (table 3.3, 3.4). Therefore, the prone position employed in the present study may not have been appropriate to assess changes in the angle of peak torque production following the training intervention and the seated positioned employed by Brockett *et al.* (2001) and Clark *et al.* (2005) may have been more appropriate. Also, the power sample calculations from the present study imply that the number of participants employed in the present study were not sufficiently high to report the minimum difference from statistical null (Appendix A), and therefore with a larger sample size a significant difference may have been reported. In addition, both Brockett *et al.* (2001) and Clark *et al.* (2005) reported isokinetic strength at an angular velocity of 60°/s. The current study reported isokinetic strength assessments from three different angular velocities, the fastest being 240°/s. To avoid the effects of acceleration and deceleration of the lever arm on torque output, only peak torque data obtained from the period of constant velocity, within a 5% range of the preset angular velocity, were analysed. At the faster angular velocities (240°/s) the lever arm will spend more of the range of motion accelerating; therefore the participants may have not been able to engage their hamstrings fully until the more extended knee joint positions. If the angle of peak torque production in the current study had been assessed at only the lowest angular velocity (60°/s) the results may have been similar to the findings of Brockett *et al.* (2001) and Clark *et al.* (2005) (refer to table 4.2, angular velocities 60°/s). These differences in test protocols between the present study and the studies which have detected a shift in the angle of peak torque production for the hamstrings following eccentric training (Brockett *et al.,* 2001; Clark *et al.,* 2005) are recognised. Consequently, a test protocol utilising slower angular velocities (i.e., 60°/s) with the participants seated on the isokinetic dynamometer may have been a more appropriate test protocol than the range of angular velocities during a prone position used in the present study to detect shifts in the angle of peak torque for the hamstrings following the training intervention. Although based on the finding from this study I would recommend that isokinetic strength assessment should be performed in an eccentric mode when detecting shifts in the angle of peak torque for the hamstrings following a training intervention.

5.2 Practical Application

Hamstrings strains are a common injury in sports that combine fast explosive sprinting and kicking activities (Garrett, 1996; Stanton and Purdam, 1989). Within soccer the hamstrings strain injury has consistently been documented as the most prevalent injury at both junior and senior level (Hawkins and Fuller, 1999; Hawkins *et al.,* 2001; Woods *et al*., 2002; Price *et al*., 2004). A weakness in the hamstrings muscles (Stanton and Purdam, 1989) and an imbalance in the hamstrings to quadriceps ratio (Croisier *et al.,* 2002; Croisier *et al.,* 2008) have consistently been documented as a plausible causative factor for a hamstring strain injuries. Furthermore recent evidence suggests that protocols designed to mimic soccer match play lead to a reduction in the hamstrings to quadriceps ratio later in the game (Rahnama *et al.,* 2003; Greig, 2008) and that the hamstrings muscle is not sufficiently stimulated by conventional soccer training and match play (Iga *et al.,* In Press). Consequently, it seems crucial to implement training programmes designed to correct abnormalities in strength imbalances through increasing hamstrings strength in soccer players (Croisier *et al.,* 2002; Croisier *et al.,* 2008). It is also well documented that the majority of hamstring strain injuries occur during the late swing phase of the running action, when the hamstrings are activated eccentrically to assist hip extension while preventing knee hyperextension (Garrett 1996). Therefore, training to incorporate eccentric muscle strength appears appropriate. In accordance with the principle of training specificity, it seems crucial to develop eccentric modes of training of the hamstrings to prevent soccer players being susceptible to hamstrings strain injuries, and the findings from this study suggest that the NHE meets this challenge.

The NHE has received some recent criticism regarding its practical application into a strength training programme for the hamstrings (Brughelli and Cronin, 2007). However, the results from the present study suggest that these criticism were not warranted and that both the stronger and weaker limbs contribute to the NHE equally, shown by no significant difference in the EMG activity of DOM and NDOM hamstring muscle groups during the movement. Also, a training programme incorporating the NHE not only increases the eccentric strength of the hamstrings, but the strength gains are not significantly different between limbs. In addition, the EMG data also illustrates that the hamstrings muscles are activated at the more extended knee joint positions. The NHE may be of more practical use than traditional hamstrings exercises for preventing and rehabilitating hamstring strain injuries as this is the knee angle at which most injuries occur. Further to this, training with the NHE appears not to result in velocity specific adaptations, which implies that training at a slow angular velocity (i.e., the NHE) could provide protection against injuries that occur during sporting activities like running where angular velocity can reach in excess of 300°/s (Knapik *et al.,* 1991).

5.3 Recommendation for further research

Based on the findings from the present study, an area of future research would be to design an investigation to compare the EMG activity in the hamstrings during the NHE between participants that can engage their hamstrings through the full range of motion and participants that can't. This study will serve to investigate if the increase in EMG activity of the hamstrings at the more extended knee joint positions is due to an increase in angular velocity due to a loss of control in the movement or if it is the increased effects of gravity in the more extended joint positions in the movement that leads to an increase in EMG activity in the hamstrings. This study could also investigate through isokinetic strength assessments if increasing the angular velocity at which the NHE is performed, leads to an increase or decrease in eccentric hamstring strength compared to training with the NHE at slower angular velocities.

A second area of suggested research regarding the NHE would be to design an investigation to compare if the internal external rotation of the participant's feet leads to alterations in the involvement of the LAT and MED hamstrings. The results from this study would demonstrate if the foot position of the participant needs to be standardised to eliminate a greater contribution of either the LAT or MED hamstrings during the NHE. The findings from this investigation would be especially important when incorporating the NHE as part of a resistance training programme, as long term training without a standardised foot position may serve to increase potential hamstrings strength asymmetries.

A further area of future research would be to design an investigation that reports both EMG activity and isokinetic eccentric strength within the hamstrings muscle group during stages of a training programme incorporating the NHE. This investigation would serve to investigate alterations in neuromuscular activity and how the hamstring muscle groups adapt during the course of the training programme. The results from Brockett *et al.* (2001) study reported muscle adaptation after a single bout of eccentric exercise incorporating the NHE represented by a shift in peak torque production to longer muscle lengths. Likewise, the present study demonstrated similar eccentric strength increases compared with previous studies (Askling *et al.*, 2003; Mjølsnes *et al.*, 2004) with a significantly shorter training period (four weeks). This investigation would serve to answer the question of the time duration needed to illicit significant increases in eccentric hamstrings strength during a training programme incorporating the NHE.

A study designed to investigate the reliability of hamstring strength assessments performed upon the isokinetic dynamometer in both seated and prone positions investigating the results from a range of different angular velocities, would serve to answer the question which is the most appropriate protocol to employ when assessing changes in the eccentric strength of the hamstrings. Also, this study could investigate which mode of isokinetic assessment (concentric or eccentric) is most appropriate to assess alterations in the length tension relationship of the hamstrings following a training intervention incorporating eccentric hamstrings training.

5.4 Conclusion

The findings from the present study suggest that the NHE is an appropriate eccentric based exercise to introduce into a strength training programme designed to reduce hamstring strain injuries in professional soccer players. This study demonstrated through electromyography that during the NHE the MED and LAT hamstrings of the DOM and NDOM limbs are engaged similarly, with the hamstrings being engaged to a greater extent at the more extended knee positions. This suggests that the NHE not only engages the hamstrings to a greater degree at the knee angle where most hamstring injuries appear to occur but the NHE will not exacerbate existing bilateral strength asymmetries between muscles and limbs. The isokinetic eccentric strength assessments from the present study confirm this supposition, as training with the NHE served to increases the eccentric strength of the hamstrings symmetrical across limbs. In addition, the present study demonstrated that training with the NHE at slower angular velocities does not result in velocity specific adaptations, as increases in eccentric hamstring strength were recorded at much faster angular velocities in both limbs. This suggests that a training programme incorporating the NHE is appropriate to prescribe an individual to provide protection against injuries that may occur during running activities where angular velocities can exceed 300°/s. Additionally, the NHE is an exercise that can be performed as part of a warm- up, and therefore time dedicated to technical and tactical aspects of the game will not be jeopardised. This study was the first of its kind to identify significant increases in eccentric hamstring strength after only four weeks of training incorporating the NHE. This would suggest that the NHE could be included as part of a pre season training modality to provide protection against hamstring strains in the competitive season.

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APPENDICIES

Appendix A

Statistical power calculations for sample size

Sample size estimation based on the hamstrings eccentric peak torque production to distinguish the minimum clinically important difference from the statistical null with an alpha level of 0.05.

Note sample size estimation formula: $N = \underline{2SD^2 (Z^{\alpha} + Z\beta)^2}$

	Velocity (°/s)		
Power	60	120	240
0.8	77	139	276
0.5	34	61	121

Z^{α} = Alpha level (0.05)
$Z\beta$ = Power
Δ^2 = The difference between the two mean values being compared
SD = The standard deviation of the two groups
N = Approximate sample size estimated

Sample size estimation based on the hamstrings angle of peak torque production to distinguish the minimum clinically important difference from the statistical null with an alpha level of 0.05.

	Velocity (°/s)		
Power	60	120	240
0.8	471	49	17
0.5	206	21	8

Note sample size estimation formula: $N = \frac{2SD^2 (Z^{\alpha} + Z\beta)^2}{\Delta^2}$

Z^{α} = Alpha level (0.05)
$Z\beta$ = Power
Δ^2 = The difference between the two mean values being compared
SD = The standard deviation of the two groups
N = Approximate sample size estimated

Appendix B

Participant information sheets

Participant Information Sheet

Name of experimenter: Steven Fruer

Supervisors: Dr. John Iga, Dr. David James and Dr. Martine Deighan

Title of study:

Effects of "Nordic" hamstring exercise training on the neuromuscular functioning of the hamstrings muscle group.

Purpose of the study

Team sports such as soccer, rugby and hockey are associated with a high incidence of hamstrings muscle strain injuries (Hawkins and Fuller, 1999; Woods *et al.,* 2004: Price *et al.,* 2004). Most of these injuries are sustained whilst running or sprinting as the hamstrings muscle group work eccentrically (i.e. lengthen whilst generating tension) to prevent knee hyperextension and hip extension (Price *et al.,* 2004). It has been suggested that a relative weakness in the eccentric strength of the hamstring muscles may predispose to injury (Garrett, 1996): it may be that by resistance training to increase the eccentric strength of the hamstrings, the threat and severity of a hamstring muscle strain injury may be limited.

In accordance with the principle of training specificity, to induce optimal developments in the eccentric strength, resistance training methods that emphasis an eccentric overload should be utilised. Specialised resistance training machines designed to train the hamstring muscles during eccentric actions are now commercially available (http://www.yoyotechnology.com/sport.html). Although excellent results in terms of injury prevention and improved sprint performance have been reported following training using this device (Askling *et al.*, 2002), these training machines are relatively expensive and may not be affordable at many clubs.

An exercise that has received increasing amount of interest in recent years as a means of training to increase the eccentric strength of the hamstrings is the "Nordic" hamstrings exercise. The main attraction of this exercise is that it is a simple partner assisted exercise that requires no additional equipment and can be performed with a squad of players in the "field". A significant improvement in the eccentric strength of the hamstring muscles has been reported following training using this exercise (Mjølsnes *et al.*, 2004). Additionally, one group of researchers reported a significant reduction in the incidence and severity of hamstring injuries following the incorporation of this exercise into the existing strength training routines of professional rugby union players (Brooks *et al.*, 2006).

Despite such positive observations, to date, no research group has considered changes in the neuromuscular activity of the hamstrings following training with this "Nordic" hamstrings exercise. Consequently, the aim of this study is to analyse how the hamstring muscles recruitment characteristics during the "Nordic" hamstring exercise change through a training period.

Procedures and participants role

Training programme

Figure 1 provides a schematic representation on the study design. Twenty male team sports players will be randomly assigned into either a training group or a non-training group. The formal training programme will last for 4 weeks, during which time participants will be allowed to continue with their normal team sports training but will be asked to refrain from any other resistance based training. The training group will be required to follow a four week programme of resistance training incorporating the "Nordic" Hamstring Exercise. The "Nordic" Hamstring Exercise will be fully explained to all participants before training commences. This programme will be progressively increased throughout the course of the training programme to ensure progressive overload. The principal investigator will be present to supervise at all training sessions. The non-training group will be required to perform one set of the "Nordic" Hamstring Exercise in weeks one and four of the training programme.

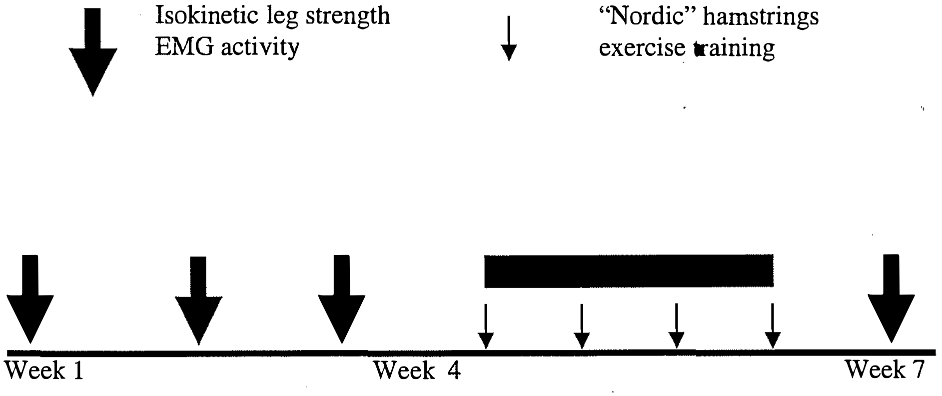


Figure 1. Schematic representation of the study design.

Test Procedures

All participants will be required to visit the physiology laboratory on three separate occasions prior to the training phase and once after the training period. During these visits, after a period of warming-up, special electrodes will be taped to the back of the thigh; these electrodes will be used to measure the electrical activity of the hamstrings muscles during the strength assessments. Participants will then be asked to perform a series of strength assessment. The strength assessments will be made during about 20 maximal efforts, performed at a range of test velocities in both your dominant and non-dominant limb. These exercises will be performed on a special testing machine and are quite safe.

Please Note:

All participants have the right to withdraw from the project/study at any time without prejudice to access of services, which are already being provided or may subsequently be provided to the participant.

Appendix C

Informed consent form

UNIVERSITY OF
GLOUCESTERSHIRE

SPORT & EXERCISE LABORATORIES

Informed Consent Form

Description of study:

Effects of “Nordic” hamstring exercise training on the neuromuscular function of the hamstrings muscle group.

I agree to participate in the study listed above, the nature of which has been clearly explained to me.

The purpose and details of this study and research procedures have been explained to me.

I understand the scope of my involvement in this study and that I have the right to withdraw from this study at any time for any reason, and that I will not be required to explain my reason for withdrawing.

I understand that all the information I will provide will be treated in strict confidence.

I have had the opportunity to ask questions regarding my participation.

Name:

Signed: .... Date:

Name of Guardian*:

Signed*: .... Date*

Tester:

Signed: .... Date:

*to be completed only if the participant is under 18 years of age

Appendix D

Pre exercise health questionnaire

UNIVERSITY OF
GLOUCESTERSHIRE

SPORT & EXERCISE LABORATORIES

Health Questionnaire

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

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

Section 1: The testing (completed by tester)

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

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

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

The testing involves:

Walking ☐
Running ☐
Cycling ☐
Rowing ☐
Swimming ☐
Jumping ☐

Generating or absorbing high forces through your arms ☐
Generating or absorbing high forces through your shoulders ☐
Generating or absorbing high forces through your trunk ☐
Generating or absorbing high forces through your hips ☐
Generating or absorbing high forces through your legs ☐

Section 2: General information

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

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

Section 3: Initial considerations

		No	Yes
1.	Do any of the following apply to you?		
a)	I have HIV, Hepatitis A, Hepatitis B or Hepatitis C		
b)	I am pregnant		
c)	I have a muscle or joint problem that could be aggravated by the testing described in section 1		
d)	I am feeling unwell today		
e)	I have had a fever in the last 7 days		

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

Section 4: Habitual physical activity

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

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

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

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

Section 5: Known medical conditions

4. Do **any** of the following apply to you? No Yes
   a) I have had insulin-dependent diabetes for more than 15 years
   b) I have insulin-dependent diabetes and am over 30 years old
   c) I have non-insulin-dependent diabetes and am over 35 years old

5. Have you ever had a stroke? No Yes

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

7. Do **both** of the following apply to you? No Yes
   a) I take asthma medication
   b) I have experienced shortness of breath or difficulty with breathing in the last 4 weeks?

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

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

Section 6: Signs and symptoms

9. Do you often have pains in your heart, chest, or the surrounding areas? No Yes

10. Do you experience shortness of breath, either at rest or with mild exertion? No Yes

11. Do you often feel faint or have spells of severe dizziness? No Yes

12. Have you, in the last 12 months, experienced difficulty with breathing when lying down or been awakened at night by shortness of breath? No Yes

13. Do you experience swelling or a build up of fluid in or around your ankles? No Yes

14. Do you often get the feeling that your heart is racing or skipping beats, either at rest or during exercise? No Yes

15. Do you regularly get pains in your calves and lower legs during exercise that are not due to soreness or stiffness? No Yes

16. Has your doctor ever told you that you have a heart murmur? No Yes

17. Do you experience unusual fatigue or shortness of breath during everyday activities? No Yes

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

Section 7: Risk factors

18. Does **either** of the following apply to you? No Yes

   a) I smoke cigarettes on a daily basis
   b) I stopped smoking cigarettes on a daily basis less than 6 months ago

19. Has your doctor ever told you that you have high blood pressure? No Yes

20. Has your doctor ever told you that you have high cholesterol? No Yes

21. Has your father or any of your brothers had a heart attack, heart surgery, or a stroke before the age of 55? No Yes

22. Has your mother or any of your sisters had a heart attack, heart surgery, or a stroke before the age of 65? No Yes

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

   a) I have had insulin-dependent diabetes for less than 15 years
   b) I have insulin-dependent diabetes and am 30 or younger
   c) I have non-insulin-dependent diabetes and am 35 or younger

Section 8: Signatures

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

Guardian*: Date: ………………………

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

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

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

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

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

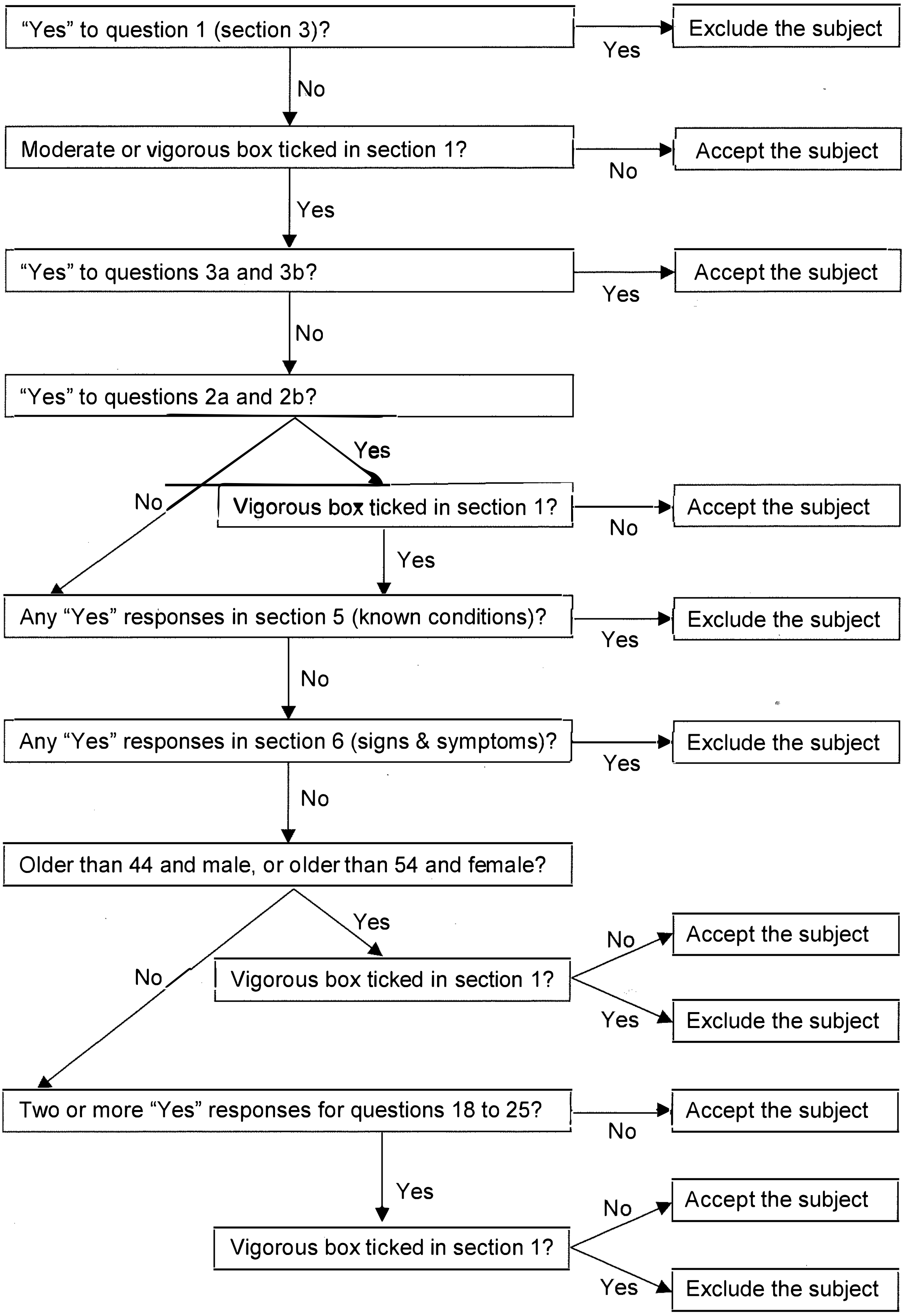
26. Is the participant eligible for the testing? No Yes

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

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

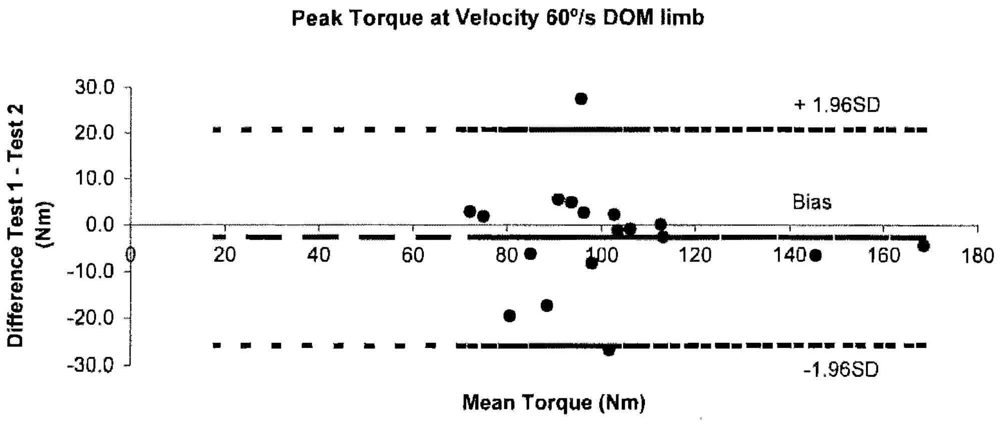
Appendix 7

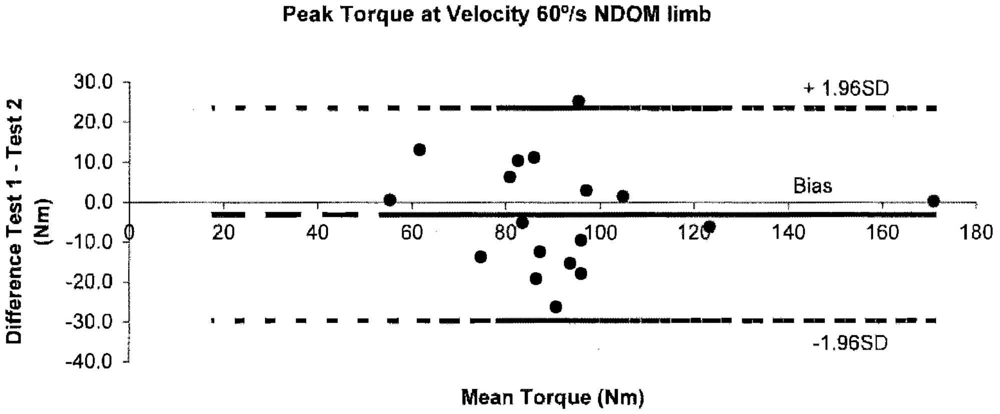
Processing the completed questionnaire – a flow diagram

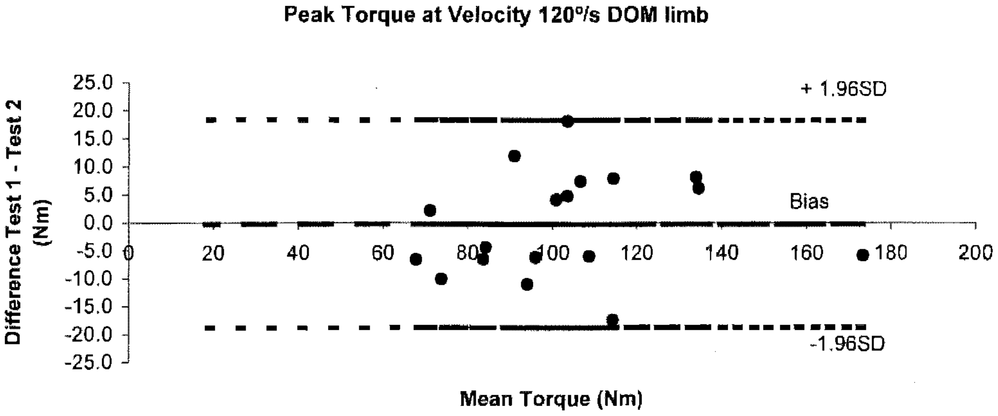


Appendix E

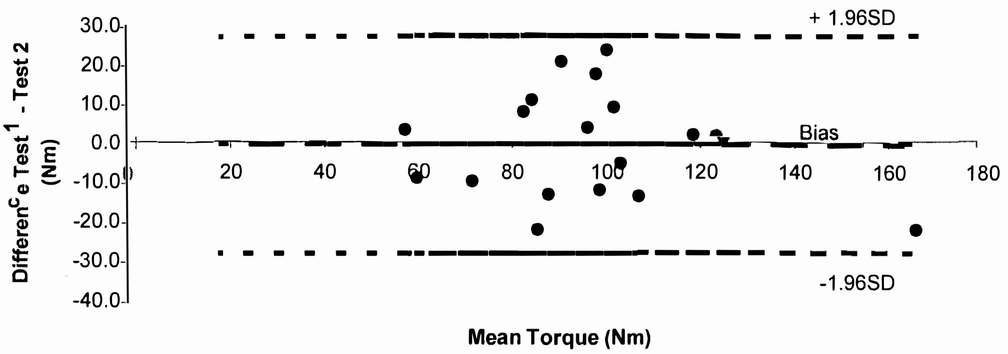
Bland-Altman plots for reliability trials


Peak Torque at Velocity 60°/s DOM limb

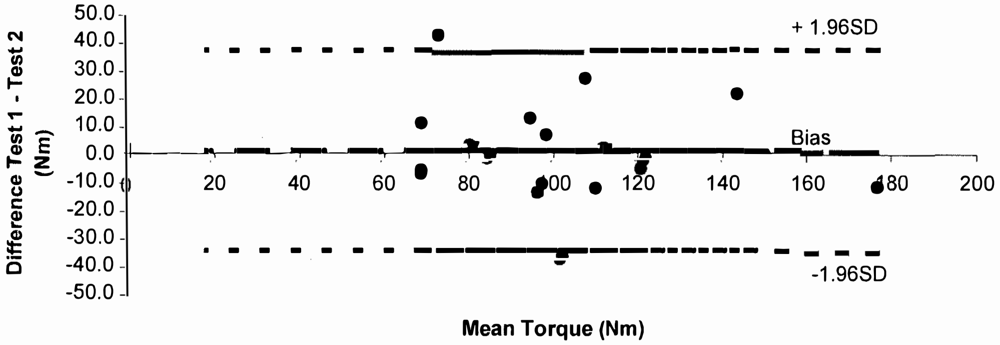

Peak Torque at Velocity 60°/s NDOM limb


Peak Torque at Velocity 120°/s DOM limb

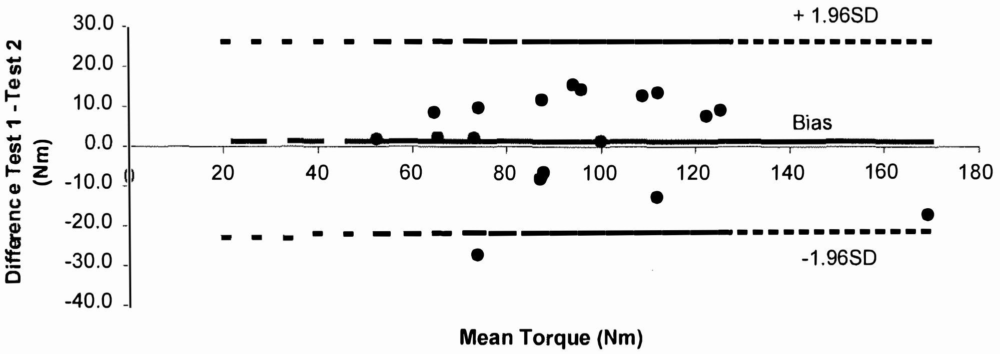
Peak Torque at Velocity 120°/s NDOM limb

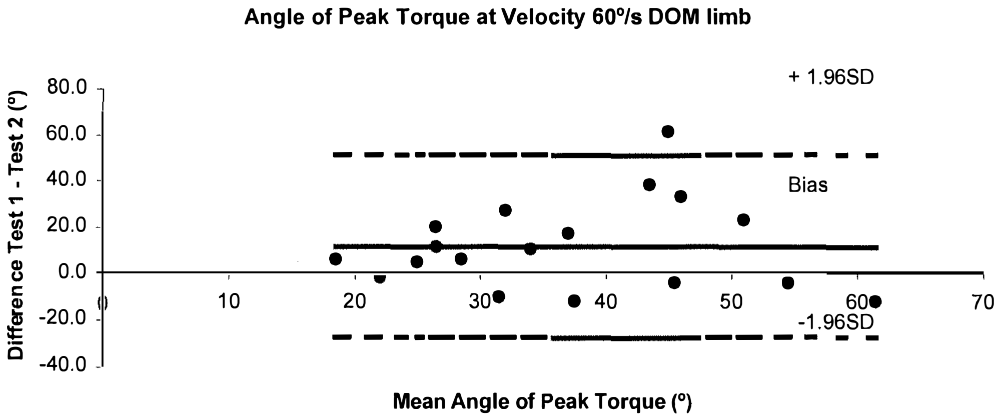


Peak Torque at Velocity 240°/s DOM limb

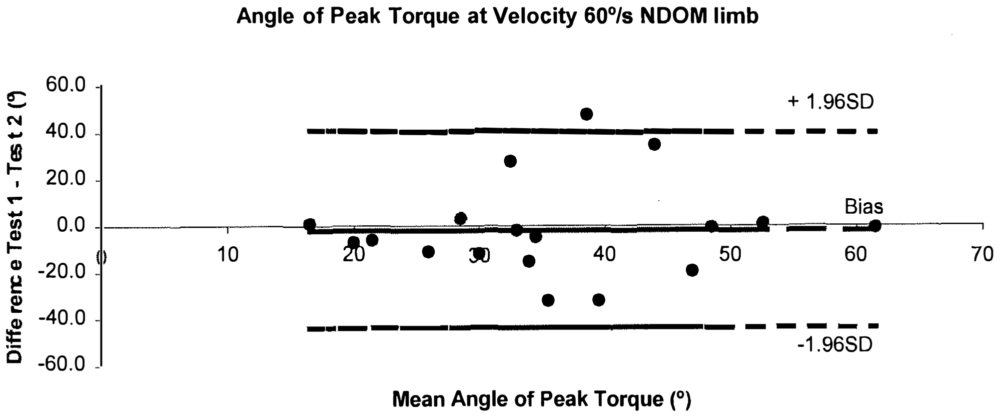


Peak Torque at Velocity 240°/s NDOM limb

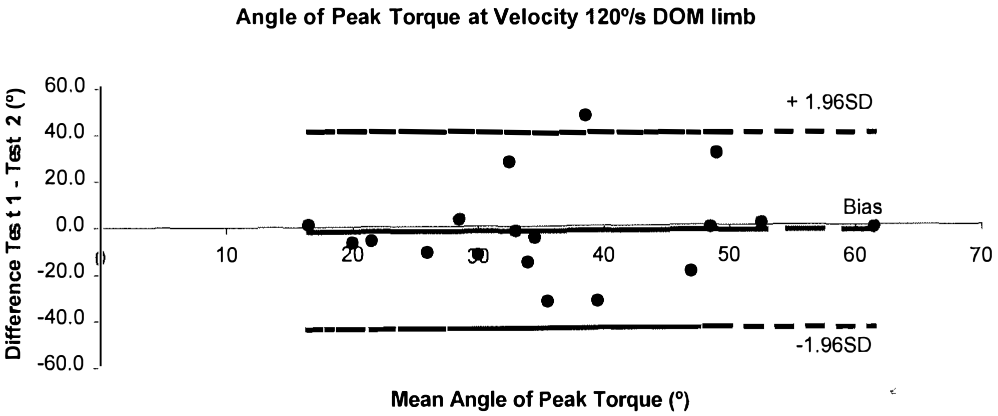




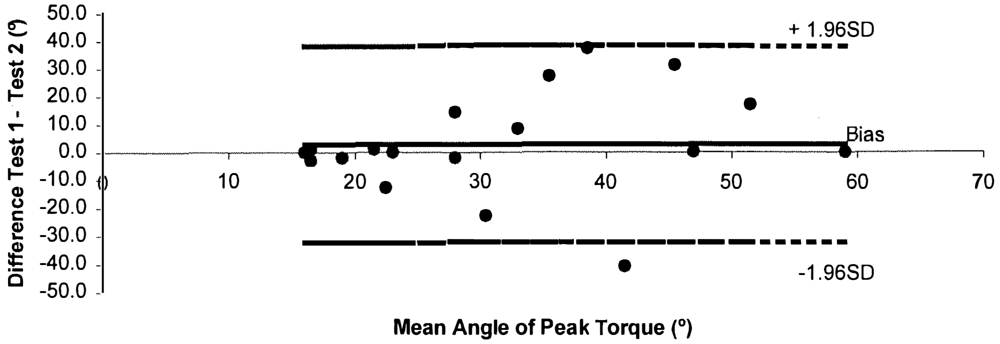
Angle of Peak Torque at Velocity 60°/s DOM limb

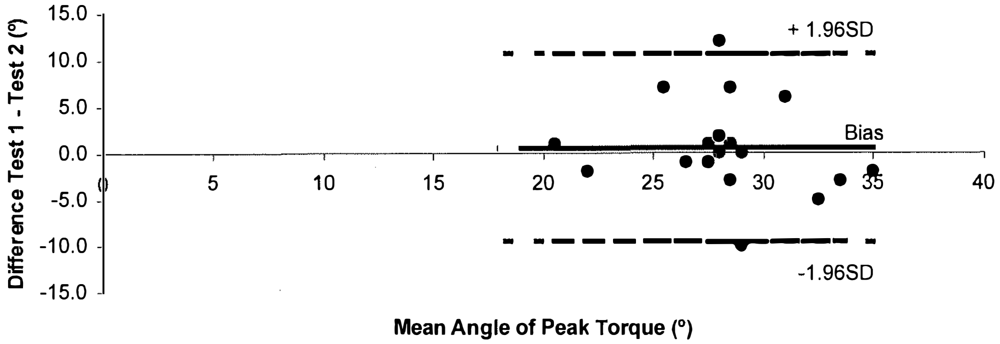


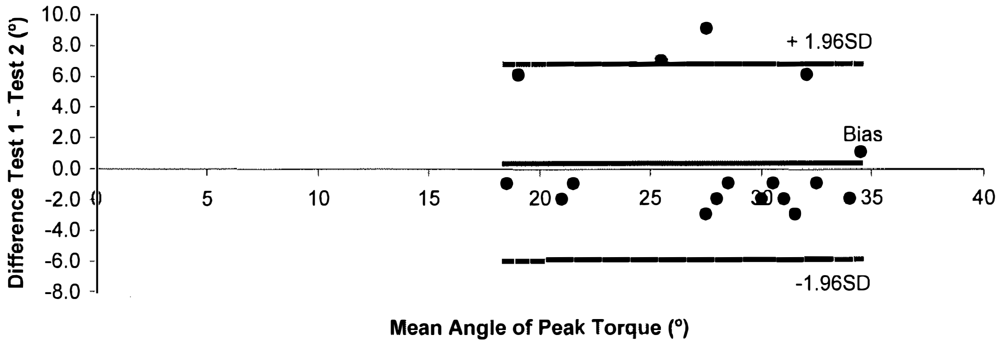
Angle of Peak Torque at Velocity 60°/s NDOM limb



Angle of Peak Torque at Velocity 120°/s DOM limb


Angle of Peak Torque at Velocity 120°/s NDOM limb


Angle of Peak Torque at Velocity 240°/s DOM limb


Angle of Peak Torque at Velocity 240°/s NDOM limb

Appendix F

NHE Electromyography data

		DOM		NDOM	
Subject	Phase	LAT	MED	LAT	MED
2	1	7.8	5.6	4.1	5.9
	2	15.7	16.4	12.4	18.3
	3	10.8	10.4	7.3	9.9
3	1	1.6	2.4	1.7	1.7
	2	2.9	4.4	2.2	4.8
	3	4.2	5.4	4.3	5.6
4	1	1.8	3.3	2.1	5.9
	2	10.9	15.9	9.9	18.2
	3	10.9	8.9	12.1	15.1
7	1	7.0	4.1	6.3	9.3
	2	12.6	13.8	11.3	14.7
	3	10.1	10.0	14.9	14.0
8	1	4.6	4.9	2.1	4.7
	2	14.3	14.2	4.5	14.7
	3	6.1	5.8	3.0	8.9
9	1	0.8	6.4	2.4	5.1
	2	2.1	15.4	6.7	14.3
	3	4.2	12.6	7.1	15.3
10	1	1.1	1.6	3.5	3.1
	2	5.6	7.6	7.4	10.8
	3	8.2	8.1	9.5	13.6
12	1	5.7	5.5	5.3	8.0
	2	13.1	13.9	9.7	13.4
	3	8.4	12.3	7.2	11.6
14	1	5.1	5.6	5.0	5.1
	2	12.7	13.1	12.7	11.3
	3	13.9	11.1	15.0	13.4
16	1	2.9	3.3	4.5	10.1
	2	8.8	8.1	9.2	14.1
	3	9.3	6.4	10.6	16.5
17	1	4.4	5.7	6.1	4.1
	2	13.1	16.1	14.7	11.2
	3	8.2	9.8	10.9	8.7
18	1	2.0	4.1	3.4	2.3
	2	10.0	14.9	11.1	4.6
	3	9.7	11.0	7.9	4.5
19	1	3.4	1.4	2.5	2.2
	2	7.5	4.0	6.4	5.0
	3	6.1	2.5	6.5	5.4
20	1	2.2	4.8	0.8	4.4
	2	10.8	13.7	3.2	11.3
	3	8.6	7.6	4.5	9.3
21	1	3.0	3.3	3.6	3.9
	2	12.4	8.9	11.5	8.0
	3	6.7	4.8	6.6	8.3
22	1	4.1	5.8	3.5	9.6
	2	10.0	14.2	9.0	18.1
	3	9.1	9.2	10.7	14.2
23	1	2.1	3.6	3.8	7.6
	2	7.5	15.1	16.1	18.3
	3	4.4	5.0	7.1	9.3
26	1	1.7	2.1	1.2	2.0
	2	12.3	11.6	5.6	14.0
	3	11.5	9.0	6.8	11.4

Appendix G

Isokinetic hamstring data

Experimental

	60 °/s							
	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
12	108	13	92	41	145	16	139	15
14	216	19	159	20	227	38	185	15
16	63	66	48	69	88	26	55	55
17	115	20	106	20	129	17	107	19
18	101	54	106	30	123	35	122	30
19	83	62	72	47	75	76	76	32
20	101	35	98	29	107	25	120	24
21	118	24	95	33	122	38	107	34
22	100	25	85	41	139	17	131	16
23	148	23	131	13	169	18	152	22

	120 °/s							
	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
12	116	15	86	29	127	18	130	17
14	219	18	160	17	230	21	165	21
16	68	59	56	57	103	16	57	59
17	129	16	112	18	134	17	115	15
18	102	32	125	28	134	18	142	16
19	80	61	88	24	73	62	83	35
20	94	62	114	17	112	15	117	18
21	133	16	86	28	140	15	106	22
22	101	16	80	63	121	17	124	15
23	169	16	145	15	170	17	157	16

	240 °/s							
	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
12	106	29	89	33	114	29	126	28
14	213	27	166	33	224	24	182	33
16	69	32	44	33	98	20	61	34
17	117	23	112	21	122	23	120	22
18	135	28	130	21	143	22	139	29
19	85	34	95	33	74	26	88	30
20	90	28	91	30	114	27	117	20
21	134	21	81	29	135	21	114	29
22	95	28	82	32	110	27	120	29
23	160	28	133	21	170	27	147	21

Control

60 °/s

	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
2	83	27	73	20	108	35	95	25
3	126	30	124	51	148	23	126	52
4	116	22	106	13	102	24	97	13
7	142	15	114	22	136	16	117	13
8	73	44	75	18	66	21	78	26
9	104	63	78	53	105	48	86	35
10	197	16	186	13	174	15	168	13
26	119	21	99	23	124	16	107	21

120 °/s

	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
2	75	46	62	27	101	17	88	28
3	145	21	135	30	151	22	123	60
4	102	16	91	15	115	18	96	16
7	142	16	112	16	145	16	110	19
8	81	16	81	17	72	19	93	19
9	106	61	86	54	84	63	87	30
10	196	16	180	17	174	16	172	16
26	132	20	93	30	124	16	108	29

240 °/s

	Pre				Post			
	DOM		NDOM		DOM		NDOM	
Subject	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)	Torque (Nm)	Angle (°)
2	89	27	68	29	97	34	92	32
3	152	34	135	34	148	27	133	34
4	90	28	90	20	100	27	97	29
7	136	21	108	23	122	29	93	32
8	82	30	78	26	70	27	87	27
9	48	35	79	48	46	35	79	26
10	190	22	169	22	173	27	160	22
26	128	29	98	29	124	23	113	30