HAMSTRING STRAIN INJURIES:
UNDERSTANDING RISK FACTORS AND INTERVENTION STRATEGIES

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Hamstring Strain Injuries:
Understanding Risk Factors and Intervention Strategies

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The contributions of the co-authors are as follows:

- Associate Professor Kong, Professor Folland, Dr Pain and Dr Lim provided the initial project direction and edited the manuscript drafts.
- I prepared the paper drafts and subsequent revisions. The manuscript was revised by Associate Professor Kong, Professor Folland and Dr Pain.
• I co-designed the study Associate Professor Kong, Professor Folland and Dr Pain; and performed all the laboratory work at the Sports Biomechanics Laboratory, Physical Education and Sports Sciences, National Institute of Education.

• I was responsible for the data collection and analysis.

• Dr Lim assisted in providing training for ultrasound usage and interpretation.


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• I was responsible for the data collection and analysis.
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Hamstring strain injuries (HSI) is a common lower-limb injury sustained by many athletes of sprint-based sports (e.g. football) throughout the course of their career. In several large-scale studies looking at the prevalence of injuries over a competitive playing season, it was found to be the most prevalent injury sustained by players. The high recurrence rates associated with HSIs further exacerbates its problematic nature. Consequently, HSIs have been found to result in high individual and financial costs to the athlete and the support systems surrounding him or her. Therefore, the purpose of this programme of research was to understand the risk factors associated with HSIs and examine the characteristics of different hamstring strengthening exercises that are commonly prescribed. Another purpose of this study was to understand if an intervention designed to address injury-mechanism related parameters (e.g. weakness in eccentric strength at longer muscle lengths) could effectively reduce the susceptibility to HSIs. In order to meet the purposes set out in this research study, three separate experimental studies were designed and conducted.

In the first study, structural and functional characteristics of the hamstrings were compared between athletes who previously sustained an HSI and those who were uninjured. The objective of this study was to determine characterisations of a previously-injured hamstring muscle which might be interpreted as possible risk factors. The results of the study suggested that previously-injured hamstrings had shorter muscle fascicles and were more pennate; and were generally stiffer. Subtle differences in sprinting kinematics relating to hip flexion angle were also observed. Additionally, inter-session reliability measures of architectural and viscoelastic assessments also found ultrasonography and myotonometry to be reliable as structural measures of the hamstring.
The objective of the second study was to examine the muscle activation characteristics of a range of hamstring strengthening exercises. Besides looking at commonly prescribed exercises such as the Nordic Hamstring Lowers (NHL), variations of exercises were also examined. These variations were designed based on current understanding of the mechanism of HSIs (e.g. state of muscle during onset of injury). In this study, it was found that despite the high muscle activation levels elicited during the NHL, it was typically performed when the muscle was under minimal elongation stress. On the other hand, Lengthened-state Training (LST) exercise, more specifically, a seated-leg curl performed with the hip flexed at 60° elicited high muscle activation levels accompanied by the greatest amount of elongation stress. This suggested that LST could be a more effective hamstring strengthening exercise than what is currently widely prescribed.

By utilising the results of the second study, the objective of the final study was to determine if a training intervention utilising LST would be effective in modifying the muscle architecture and eccentric strength measures identified as possible risk factors from the first study. In this study, 43 participants underwent a 12-week intervention programme consisting of control (CON), NHL or LST training. Muscle architecture and eccentric strength was measured pre and post training. It was found that in participants in both training groups, there was significant hypertrophy of the muscles reflected in an increase in muscle thickness, however, these changes were not accompanied by changes in fascicle length and pennation angle. There was also a larger eccentric strength increase in the LST compared to the NHL, suggesting that LST could be more effective than NHL in reducing injury risk.

Thus, this research study suggests that muscle structure and function could be modifiable risk factors of HSI that can be addressed through a strengthening programme that is designed to strengthen the muscle at the state (contraction type and muscle length) at which
the injury commonly occurs. This could have implications for approaches to designing
training interventions for reducing the risk of a range of muscular injuries.

**Keywords:** muscle architecture, function, differences, biceps femoris, semitendinosus,
characteristics, training, strengthening,
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Presentations:


Published abstracts:

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<tr>
<td>AN</td>
<td>assisted nordics hamstring lowers</td>
</tr>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
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<tr>
<td>ANCOVA</td>
<td>analysis of covariance</td>
</tr>
<tr>
<td>BF</td>
<td>biceps femoris</td>
</tr>
<tr>
<td>BFlh</td>
<td>biceps femoris long head</td>
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<tr>
<td>BFsh</td>
<td>biceps femoris short head</td>
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<tr>
<td>CI</td>
<td>confidence interval</td>
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<tr>
<td>CL</td>
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<td>ConPT</td>
<td>concentric peak torque</td>
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<td>electromyography</td>
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<td>fascicle length</td>
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<td>GM</td>
<td>“Good morning’</td>
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<td>HSI</td>
<td>hamstring strain injuries</td>
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<td>IHE</td>
<td>inclined hip extension</td>
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<td>IL</td>
<td>injured limb</td>
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<td>LST</td>
<td>lengthened-state training</td>
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<td>MRI</td>
<td>magnetic resonance imaging</td>
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<tr>
<td>MT</td>
<td>muscle thickness</td>
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<tr>
<td>NHL</td>
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<td>PA</td>
<td>pennation angle</td>
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PT – peak torque

SHE – straight-leg hip extension

SLC – seated leg-curl

ST – semitendinosus

SM – semimembranosus

UL – uninjured limb
Chapter 1: Introduction

1.1 Background

1.1.1 General anatomy. The hamstrings is a collective term describing three muscles on posterior part of the thigh (Figure 1.1). On the lateral side, it comprises the biceps femoris long and short head (BF); and on the medial side, it consists of the semitendinosus (ST) and semimembranosus (SM). The ST and SM are often termed collectively as the medial hamstrings.

The hamstrings play an important role in many locomotive activities such as walking, running, jumping, and stabilising the trunk because it crosses both the hip and knee joints. In walking and running, they serve as the antagonist to the quadriceps to aid in the deceleration of knee extension.

![Figure 1.1 Relative sites of different hamstring muscles on posterior thigh.](Source: http://teachmeanatomy.info/)
1.1.2 Hamstring strain injuries (HSI). Injuries to the hamstring are multi-factorial, therefore, provision of an accurate prognosis is often challenging. HSI are often diagnosed based on clinical and/or through ultrasonography examinations. The most common site of injury is the long head of the BF with 53% of all hamstring strains reported to occur at this muscle (Woods et al., 2004). It has been suggested that hamstring injuries are often sustained during the eccentric action phase of the muscle during movement (Garrett, 1990). This is possibly due to the non-uniform lengthening of sarcomeres, which results in damage to the muscle fibre (Morgan, 1990). Whilst the inciting event/mechanism of a HSI has been relatively well investigated, the risk factors of injury must also be explained in order to reduce an individual’s susceptibility to injury.

1.1.3 Risk factors. There are several unmodifiable risk factors of HSIs such as age (Gabbe, Bennell & Finch, 2006; Edouard et al., 2016) where every year of aging was found to be associated with a 10% increase in the risk of sustaining an injury (Arnason et al., 2004). A previous strain injury to the hamstrings has also been suggested to have the most substantial impact on the risk of reinjury. Arnason and colleagues (2012) found a 12-fold increase in the likelihood elite level football players sustaining an HSI when they were injured in the previous season. Another unmodifiable risk factor which has been studied in some detail is ethnicity although there is very little evidence to suggest a relationship between this factor and HSI risk, with only one study found which supported this suggestion; Verrall and colleagues (2001) reported that individuals of Aboriginal ethnicity were 11 times more likely to be injured than the Caucasian demographic.

Risk factors that can be modified through means such as training are known as modifiable risk factors. These include many intrinsic risk factors relating to physiological performance. Previous studies investigating the intrinsic risk factors associated with hamstrings injuries have shown that fatigue or insufficient time spent during warm-up
(Worrell, 1994), poor lumbar posture and trunk stability (Hennessy & Watson, 1993) and flexibility (Witvrouw, Danneels, Asselman, D’Have & Cambier, 2005) may result in the muscle being more susceptible to injury. External factors including activity type (Brooks et al., 2006), position on the field of play (Woods et al., 2004; Brooks et al., 2006), rate of exertion during work (Gabbe et al., 2005) have also received considerable attention. The study of these external risk factors has provided useful information on how a hamstring injury could be prevented through modifying playing behaviour. However, much lesser studies have been conducted on internal risk factors (e.g. anatomy, strength imbalance and gait characteristics) of hamstring injuries. As a result, current knowledge on how these internal risk factors influence an individual’s susceptibility to a hamstring injury is limited.

It has been postulated that the anatomy of the BF, which comprises two innervated heads could partially explain why susceptibility of the muscle site to injury is more pronounced. This feature of the muscle (double-headed) muscle may result in unco-ordinated contractions, which leads to the muscle becoming unstable (Zuluga et al., 1995). Inter-individual variability in hamstring muscle cross-sectional area (Koulouris et al., 2007; Verrall et al., 2006), as well as biceps femoris long head (BFllh) proximal aponeurosis size (Fiorentino et al., 2012) have been suggested as possible risk factors of injury.

Deficits in eccentric knee flexor strength (Lee, Reid, Elliott & Lloyd, 2009), rate of torque development (Sole, Milosavljevic, Nicholson & Sullivan, 2011) and changes in the angle of peak torque generation (Brockett, Morgan & Proske, 2004) have been found in individuals with a previous HSI. The change in the angle of peak torque being generated at shorter muscle lengths has been suggested to be a result of shorter muscle fascicles (resulting in fewer in-series sarcomeres). However, there is little evidence to suggest that shorter fascicles are an architectural feature of previously-injured hamstrings; either as an intrinsic risk factor or a consequence of injury. To date, only one retrospective study has found shorter
fascicles and larger pennation angles in the biceps femoris long head (BFlh) to be associated with previously injured hamstrings (Timmins, Shield, Williams, Lorenzen & Opar, 2015); and it has been suggested that shorter fascicles in the BF may increase an individual’s risk of sustaining a HSI (Timmins et al., 2016). However, further evidence of this association is important before future studies can proceed to establish how shortened fascicles play a role in the underlying mechanisms causing HSI.

Different muscle architecture properties have been suggested to affect the force transmission through the tendon, which results in the different loading experiences throughout the muscle-tendon unit (Thelen et al., 2005). Therefore, in order to better understand how muscle anatomy is related to the mechanism of a HSI, more careful investigations need to be conducted. However, there have been few studies conducted to investigate the risk factors associated with hamstring muscle and tendon size, shape and structure. This is likely due to the difficulty of incorporating imaging analyses in research studies when factors such as financial and temporal costs (e.g. technical training) have to be considered.

As a consequence of injury, scarring of the muscle tissue might change muscle force dissipation paths and reduce the compliance of the tendon and aponeurosis complex (Huijing, 2003). This might lead to an increase in localised tissue strains adjacent to the fibrous scar (Silder, Reeder & Thelen, 2010) and increase the likelihood of re-injury. Therefore, it is important to also understand the functional changes accompanying a change in muscle architecture after an injury. It has been found that injured hamstrings produced lower peak torque (Lee, Reid, Elliott & Lloyd, 2009) during isokinetic testing at shorter muscle lengths (Brockett, Morgan & Proske, 2004; Lee et al., 2009) compared to the uninjured side. An injured hamstring might exhibit differences in functional variables such as the length-tension
relationship, and hamstrings to quadriceps strength ratio. Therefore, there is a need to better understand hamstring function after an initial injury to assess the risk of re-injury.

As most hamstring injuries occur during running, it is possible that certain characterisations of lower-limb joint kinematics predispose an individual to injury. However, to date, limited conclusive evidence exists regarding possible characterisations. In a previous study on sub-maximal running, similar lower-limb kinematics were found between previously injured and uninjured limbs (Lee et al., 2009). Since muscle loading conditions increase with running speed (Thelen, Chumanov, Sherry & Heiderscheit, 2006), it will be useful to examine the biomechanics of injured and uninjured limbs under maximal sprint conditions found in many sports.

### 1.1.4 Interventions

Although HSI have been shown to have high individual and group costs with effective recovery being paramount, limited systematic information exists on the effectiveness of general preventive exercises for individuals who have suffered HSI. Commonly prescribed exercises include stretching, strengthening (concentric and eccentric), movement dysfunction correction, neuromuscular strategies and general intervention programmes such as warm-ups and aerobics (Goldman & Jones, 2010). The effectiveness of these interventions has been found to be mixed with some authors reporting stretching to be ineffective (Heiderscheit et al., 2010), while others recommended increasing the functional range of motion (ROM) through programmes which utilise both stretching and strengthening (Brooks, Fuller, Kemp & Reddin, 2006; Worrell & Perrin, 1992). Training targeting an improvement in balance was found to be ineffective while strengthening exercises reported conflicting results depending on the type of exercise performed (Goldman & Jones, 2010). Some authors recommended a combination of concentric and eccentric exercises (Askling, Karlsson & Thorstensson, 2008) while others deemed the use of eccentric strength training as
sufficient (Engerbretsen et al., 2010). From the aforementioned studies, it is evident that scientific opinion on the efficacy of common preventive exercises is contradicting.

A popular exercise which has been widely studied recently is Nordic hamstring lowers (NHL) exercise which involved an eccentric training modality. This exercise has been shown to decrease the incidence of HSI (Timmins et al., 2015; Bourne et al., 2015); with low eccentric strength measured during the exercise found to be associated with an increased risk of injury in some prospective studies. The mechanism through which eccentric training is able to strengthen the hamstrings is through its reported effects on increasing the fascicle lengths within the long head of the biceps femoris (Bourne et al., 2016). Due to its increasingly popular prescription as an eccentric strengthening exercise, a large body of literature has been focused on understanding its efficacy (Andersen et al., 2008; Seagrave et al., 2014), leading to limited recent published information on the efficacy and mechanisms underlying other strengthening interventions.

1.1.5 Summary. Currently, the lack of scientific evidence relating internal factors to the risk of hamstring injuries means that available risk assessment guidelines are generally incomprehensive. Systematic screening of individuals to determine hamstring injury risk should consider wide-ranging factors (both external and internal) to improve efficacy. This is important for both athletes and patients as training programmes should be individualised to maximise desired performance or functional outcomes. Therefore, there is a need for a comprehensive study specifically investigating internal risk factors of HSI to address the current gaps in literature. The results of such an investigation could be utilised to develop an effective training programme to strengthen the hamstrings to prevent injury or re-injury.
1.2 Research questions

Three main research questions formed the basis of this study. They were:

1. What were the differences in terms of muscle architecture, visco-elastic property and function between previously injured and uninjured hamstrings of athletes?

2. What were the muscle activation characteristics of different hamstrings strengthening exercises?

3. What were the effects of a hamstring strengthening programme designed to address the mechanism of injury on muscle architecture and function?

1.3 Aims and hypotheses

Three studies were planned to answer the research questions of this study. Study 1 would take place in Nanyang Technological University (Singapore) while studies 2 and 3 would take place in Loughborough University (United Kingdom).

The objective of Study 1 was to identify the internal risk factors of hamstring injuries by examining variables related to muscle architecture, muscle visco-elastic property and function (strength and running kinematics). The second part of the research was conducted in two subsequent studies (2 and 3). The objective of Study 2 was to determine an effective hamstrings-specific strengthening exercise by characterising the muscle activation pattern across different commonly prescribed and modified exercises. Study 3 was designed to evaluate the effectiveness of a training programme based on the most effective strengthening exercise determined from Study 2.
The specific aims and hypotheses corresponding to the three studies (1, 2 and 3) were:

1. **Aim:** To compare the muscle architecture, muscle visco-elastic property and function between previously injured and uninjured hamstrings of athletes.

   **Hypothesis:** Muscle architecture (muscle thickness, pennation angle and fascicle length), visco-elastic property (stiffness, decrement and oscillation frequency) and function (hamstrings to quadriceps strength ratio, muscle length-tension relationship, muscle activity and sprinting biomechanics) would differ between the limbs of previously-injured and -uninjured participants; and between contralateral limbs of previously-injured participants.

2. **Aim:** To characterise different common and modified hamstrings strengthening exercises.

   **Hypothesis:** Different exercises would exhibit different hamstring muscle activation characteristic across the biceps femoris and semitendinosus.

3. **Aim:** To evaluate the effectiveness of an injury-mechanism specific 12-week hamstrings-specific training programme.

   **Hypothesis:** The experimental group would have different muscle architecture and functional outcome variables compared to a control group and a training group utilising a commonly prescribed exercise after a 12-week training programme.
1.4 Significance of the study

This would be the first comprehensive study on HSI encompassing both identification of risk factors and a subsequent intervention programme to examine exercise-induced changes to these factors. To date, most studies investigating HSI risk factors have focused on functional variables with limited literature available on risk factors associated with muscle architecture. This is largely due to the inherent difficulty (financial and temporal costs) of taking ultrasound measurements at the hamstrings region. With current advancements in imaging technology and associated techniques, this proposed study will be one of the first to apply ultrasonography in understanding HSI in athletes. Thus, our results would likely serve as important references for future research.

The findings would also be useful in establishing training guidelines and reliable testing protocols for screening of athletes that are evidenced by research. Athletes and coaches can be better informed on how to accurately assess one’s susceptibility to hamstrings injury through the formulation of a set of assessment standards to determine injury risk. For national sporting organisations, the knowledge gathered would aid in the improvement and development of training programmes for athletes, such as implementing appropriate training methods (e.g. strengthening exercises) to minimise the risk of hamstrings injury.

1.5 Organisation of chapters

The thesis has been organised according to the following chapters

(i) Chapter 1 – Introduction
(ii) Chapter 2 – Literature review
(iii) Chapter 3 - Hamstring structural and functional differences between previously-injured and -uninjured athletes.
(iv) Chapter 4 - Muscle activation characteristics across different hamstring strengthening exercises.

(v) Chapter 5 - Architectural and functional adaptations of hamstrings following a 12-week lengthened-state training programme

(vi) Chapter 6 - General discussion
Chapter 2: Review of Literature

2.1 Methodology

The author retrieved and reviewed a range of literature that was published from February 1966 through July 2018, which included journal articles retrieved from databases including Sciverse Scopus, Pubmed, EBSCO Host, Springer Link and bibliography sections of relevant articles. In cases when access to a paper was not possible, the abstract was reviewed with awareness that full information is lacking. The keywords used in combination as part of the search strategy were “hamstring(s), biceps femoris, semitendinosus, muscle, strain, tear, injury, mechanism, cause, site, location, structure, architecture, pennation angle, orientation, fascicle, fibre, morphology, ultrasound, visco(-)elasticity, stiffness, risk factor(s), training, intervention, nordic hamstring lowers, strength, function, EMG, activity, sprint, kinematics, kinetics, isokinetic, isovelocity, isometric”. A total of 308 relevant articles, theses/ dissertations and abstracts were chosen from all return results and reviewed.

2.2 Prevalence

Hamstring strain injuries (HSI) are one of the most common types of injuries sustained by athletes involved in sports which require repetitive maximal sprinting and turning actions (e.g. football and rugby etc.). In athletics, HSIs have been found to represent close to 25% of all injuries and 75% of all injuries to the lower limbs (Opar et al., 2012). In the English Football Association’s two-year injury audit of professional footballers in the English domestic league, Woods and colleagues (2004) found HSIs to be the injury with the highest prevalence. Orchard and Seward (2002) also found that HSIs were responsible for 15% of all injuries reported in the Australian Football League. The extended rehabilitation period caused by HSIs results in time loss that affects both recreational and elite players.
Furthermore, HSIs exhibit high rates (up to 63%) of re-injury (Woods et al., 2004; Petersen et al. 2010; Elliot et al., 2011). Secondary HSIs result in more time loss than the initial injury (Ekstrand, Hagglund & Walden, 2011). In addition, there are financial consequences with the cost of an individual HSI found to be close to an average of US$96 250 in the AFL in 2012 (Figure 2.1). In the English Premier League, clubs reported a loss of close to £75 million as a result of paid wages to unavailable players as a result of injury during a single season (1999-2000) (Woods, Hawkins, Hulse & Hodson, 2002). Therefore, it is evident hamstring injuries pose a great challenge to the athlete and those involved in his/her support system.

Figure 2.1. Mean annual financial cost of hamstring injuries in Australian Rules Football.

(Hickey, Shield, Williams & Opar, 2013)
2.3 Detailed anatomy

The BF is made up of the long (BFlh) and short heads (BFsh). Apart from the BFsh which serves to flex the knee, the BFlh, SM and ST cross both the knee and hip joints. Together, they aid in both knee flexion and hip extension movements, together with external and internal rotation movements (Table 2.1).

Table 2.1. Origin and insertion points; and movements produced by each hamstring muscle.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps femoris (BF)</td>
<td>Biceps femoris long head (BFlh): Ischial tuberosity</td>
<td>Fibula head</td>
<td>Flexes knee (primarily short head); externally rotates hip when knee is flexed; extends hip</td>
</tr>
<tr>
<td></td>
<td>Biceps femoris short head (BFsh): Linea aspera, lateral supracondylar line, and distal femur</td>
<td>Lateral condyle of tibia</td>
<td></td>
</tr>
<tr>
<td>Semitendinosus (ST)</td>
<td>Ischial tuberosity</td>
<td>Medial aspect of upper tibial shaft</td>
<td>Extends hip; flexes knee; internally rotates tibia</td>
</tr>
<tr>
<td>Semimembranosus (SM)</td>
<td>Ischial tuberosity</td>
<td>Medial condyle of tibia, through oblique popliteal ligament to lateral condyle of femur</td>
<td>Extends hip; flexes knee; internally rotates tibia; pulls medial meniscus posteriorly during knee flexion</td>
</tr>
</tbody>
</table>

(Silvestri, Muda & Orlandi, 2015)

The BF has two origin locations with the origin of the BFlh on the medial side of the ischial tuberosity (IT) and the origin of the BFsh found on the lateral supracondylar ridge of the femur and the middle-third of the linear-aspera. The BFlh tendinous insertions start from the proximal knee and splits into the direct and anterior tendinous portions; and three fascial
components (lateral and anterior aponeurosis; and reflected arm,) (Terry & LePrade, 1996).
The origin of the ST is the infero-medial aspect of the ischial tuberosity as part of a joined
tendon with the BFlh and inserts into the supero-medial part of the tibia (Netter et al., 2005).
The SM originates superior and lateral to the BF; and ST originates from the ischial
tuberosity (Miller, Gill & Webb, 2007). These different points of insertions work together to
serve the important roles of knee stabilisers during different movements (Koulouris &
Connell, 2005).

Due to the challenges in conducting in vivo measurements, most studies measuring
linear dimensions of the hamstring muscles have utilised cadaver samples (Kellis, Galanis,
Kapetanos & Natis, 2012; Woodley & Mercer, 2005). To date, the use of in vivo
measurements has only been conducted on the BFlh with measurements similar to those
measured on cadaveric samples (Timmins et al., 2014; Chleboun, France, Crill, Braddock &
Howell, 2001). From the results of these studies, it has been found that muscle length is
longest in the BFlh (29.6-34.7 cm) and fascicle length is longest in the ST (13.8-19.3 cm).
The SM is the thickest hamstring muscle (cross sectional area (CSA): 18.2-18.4 cm²) and has
the most pennate muscles (15.1° to 16.0°). On the other hand, the ST is the thinnest (4.8-5.4
cm²) with smaller pennation angles (PA) (9.1-12.9°). Besides architectural differences, intra-
muscular differences at both distal and proximal ends were also found. Larger angles of
pennation (+35%, 24.0° versus 17.8°) and longer fascicles (+12%, 7.1 cm versus 6.4 cm) in
the BFlh were found at the proximal compared to distal end. (Kellis et al., 2010)
2.4 Hamstrings function during sprint-based activities

HSI have been reported to occur while the athlete is running close to maximal or maximum speeds (Askling et al., 2013, 2007). Thus, a comprehensive understanding of the biomechanical function of the hamstring muscles during high-speed running is required in order to contribute to the development of preventive strategies directed towards addressing the mechanism of injury.

Presently, most studies have assessed electromyographic (EMG) activity and/or have utilised an inverse dynamics approach to evaluate hamstring muscle function during running. In studies which have measured EMG activity of the hamstrings, it has been found that the muscle activation is highest from midswing until terminal stance (Jonhagen, Ericson, Nemeth & Eriksson, 1996; Simonsen, Thomsen & Klausen, 1985) (Figure 2.2, Weiman & Tidow, 1995). In a number of these investigations, peak activity was observed to have occurred during terminal swing (Higashihara, Kubota, Okuwaki & Fukubayashi, 2010), whereas others have found it to occur during stance (Kyrolainen, Avela & Komi, 2005). Studies have also characterised hamstring muscle function during high-speed running by utilising information from lower limb joint moments and powers derived from inverse dynamics methods (Schache et al., 2011; Simonsen et al., 1985; Wood, 1987). In these studies, the existence of a hip extensor moment was found from the midswing to early stance phase, accompanied a knee flexor moment during terminal swing phase. This combination of moments suggest that a considerable load is likely imparted onto the hamstrings during high-speed running.
Musculoskeletal studies utilising modelling methods have also shown that muscle-tendon unit stretch is correlated to running velocities of up to approximately 80% of maximum but remains stable at velocities representative of sprinting. However, the extent of strain is different between muscles. (Figure 2.3, Lai et al., 2015; Schache et al., 2013; Thelen et al., 2005)
Studies have also found that in the latter phase of running, the BF1h muscle-tendon unit undergoes the greatest change in length (with respect to standing length while upright) compared to the ST and SM muscles (Chumanov et al., 2011; Thelen et al., 2005). The largest range is observed in the ST, which is possibly a result of it having a longer moment arm during knee flexion which results in greater shortening during knee flexion. When
compared against corresponding upright lengths, the BF is stretched more than the medial hamstrings across a large range of movement velocities (Table 2.2, Thelen et al., 2005).

Table 2.2. Average (standard deviation) peak muscle-tendon lengths normalised to lengths in an upright position during the duration of a complete gait cycle.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Speed (% max)</th>
<th>$L_{\text{max}}^{a,c}$</th>
<th>$t_{\text{max}}^{a,b}$ (%GC)</th>
<th>$\Theta_{\text{hip}}^{a,b}$ (°)</th>
<th>$\Theta_{\text{knee}}^{a,b}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps femoris</td>
<td>80</td>
<td>1.098 (0.026)</td>
<td>86.9 (4.2)</td>
<td>62.7 (8.3)</td>
<td>43.9 (12.6)</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>1.096 (0.028)</td>
<td>87.1 (4.5)</td>
<td>63.1 (6.8)</td>
<td>44.3 (11.6)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>1.097 (0.027)</td>
<td>87.4 (3.8)</td>
<td>63.3 (7.1)</td>
<td>44.8 (10.2)</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>1.094 (0.027)</td>
<td>88.3 (3.5)</td>
<td>62.6 (5.8)</td>
<td>45.4 (9.9)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.098 (0.028)</td>
<td>89.6 (3.7)</td>
<td>64.6 (6.7)</td>
<td>45.4 (8.7)</td>
</tr>
<tr>
<td>Semimembranosus</td>
<td>80</td>
<td>1.077 (0.015)</td>
<td>89.9 (2.9)</td>
<td>56.6 (7.5)</td>
<td>31.4 (6.6)</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>1.075 (0.019)</td>
<td>90.4 (3.1)</td>
<td>57.2 (7.0)</td>
<td>32.1 (5.7)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>1.075 (0.015)</td>
<td>90.0 (2.7)</td>
<td>58.8 (7.4)</td>
<td>35.4 (5.2)</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>1.072 (0.015)</td>
<td>90.8 (2.4)</td>
<td>59.9 (6.4)</td>
<td>37.2 (5.6)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.075 (0.016)</td>
<td>92.0 (2.7)</td>
<td>61.4 (8.0)</td>
<td>38.4 (5.3)</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>80</td>
<td>1.084 (0.017)</td>
<td>89.7 (2.9)</td>
<td>56.9 (7.5)</td>
<td>31.8 (6.6)</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>1.082 (0.020)</td>
<td>90.1 (3.1)</td>
<td>57.5 (6.9)</td>
<td>32.7 (5.8)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>1.082 (0.017)</td>
<td>90.0 (2.7)</td>
<td>58.9 (7.4)</td>
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<tr>
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<td>92.0 (2.7)</td>
<td>61.5 (8.0)</td>
<td>38.7 (5.3)</td>
</tr>
</tbody>
</table>

$^a$ Significant muscle effects ($P < 0.01$); $^b$ significant speed effects ($P < 0.01$); $^c$ significant muscle by speed interactions ($P < 0.01$).

(Thelen et al., 2005)

In summary, all studies to date suggest that hamstrings activation is greatest during the early stance and late swing phases of running. During the late swing phase, the initiation of the stretch-shortening cycle accompanied by significant eccentric contraction of the hamstrings loads each of the different hamstring muscles differently: and during the early
stance phase, there is high concentric loading involved. The high biomechanical loading
demands on the hamstrings highlights their importance during different high-speed running
activities.

2.5 Hamstring Strain Injuries

In this section, an overview of HSI will be provided covering the mechanism and site
of injury. Both muscle architecture and function risk factors which predispose an individual
to injury will also be reviewed. The key words used during this search were 'hamstring',
'strain injury', 'mechanism', 'cause', 'site', 'location', 'risk factors', 'architecture',
'structure' and 'function(al)'. In total, 96 relevant papers, theses/ dissertations and abstracts
were chosen from all returned results and used in this section.

2.5.1 Mechanism of Injury. HSIs typically happen due to excessive stretch when the
hamstrings are in a passive state or undergoing eccentric modes of contraction accompanied
by large forces (Schache et al., 2012). HSIs are often sustained while individuals are sprinting
or performing locomotive movements which involve high cadence of the lower limbs
(Brooks, Fuller, Kemp & Reddin, 2006; Woods et al., 2004). During running efforts at high
velocities, eccentric contraction of the hamstring muscles typically occurs during the mid- to
late-swing phases (Thelen et al., 2005). This activation pattern of the muscle is mirrored in
studies utilising modelling techniques which have found that the hamstring muscle
experiences maximum stretch during the late-swing phase of the gait cycle (Chumanov,
Schache, Heiderscheit & Thelen, 2012).

Heiderscheit and colleagues (2005) further substantiated this finding through the use
of kinematic analysis methods in their study. Despite strong evidence form a larger number
of studies suggesting that the latter stages of the swing phase is when the onset of injury
occurs, a study by Orchard (2012) suggested that the early swing phase could instead be the timing of injury occurrence. This is possibly due to the large ground reaction forces acting through the hamstrings during this period. This appears counter-intuitive to the evidence presented in a large number of studies suggesting that injuries tend to occur during eccentric contraction of the muscles. Therefore, in the absence of more evidence to support the relationship between early phase muscle activation and muscle stretch failure, it could be confidently accepted that the onset of HSIs occurs during the period of mid- to late-swing phase.

**2.5.2 Site of Injury.** There is a strong agreement between the results of various studies that the BF1h is most commonly injured of all the hamstring muscles (Askling, Tengvar, Saartok & Thorstensson, 2007). In a study of elite sprinters which utilised magnetic resonance imaging (MRI), it was found that all HSIs occurred at the BF1h (Askling et al., 2007). High incidences (up to 83%) of HSI occurring at the site of the BF1h have also been reported across a number of retrospective injury studies (Hallen & Ekstrand, 2014; Malliaropoulos, Isinkaye, Tsitas & Maffuli, 2011). Although the most common site of injury has been conclusively established, little information is available regarding the next most common injury site. In a number of studies, it was found that the SM was the second most injured muscle after the BF (Koulouris & Connell, 2003; Malliaropoulos et al., 2011). However, other research groups have similar conclusions of the ST (De Smet & Best, 2000; Slavotinek et al., 2002). Askling and colleagues (2013) postulated that the contradicting findings on the ST and SM as the second most common injury site could be due to the different activation characteristics of the medial hamstrings across different activities.

In terms of injury site within a muscle, the proximal and distal myotendinous junctions (MTJ) have been identified as the most common locations of strain injuries. De Smet and colleagues (2000) concluded that the BF1h proximal MTJ was the most common
injury location; with findings supported by earlier in vitro analysis of animal muscular structures (Tidball & Chan, 1989).

**2.5.3 Risk factors.** HSIs pose a great challenge to athletes and the individuals comprising his/her support network (e.g. coaches, sport scientists etc.). Therefore, it is of huge relevance to be able to identify the risk factors associated with HSI in order to aid in the development training or intervention programmes.

External risk factors such as activity selection (Brooks et al., 2006), position on the field of play (Brooks et al., 2006), level of physical exertion (Witvrouw et al., 2003) and adequacy of warm-up and preparation procedures (Worrell, 1994) have also been well investigated. However, much lesser investigations have been conducted to examine the internal risk factors HSIs. As a result, these factors are often poorly understood.

**2.5.3.1 Architecture.**

*Fibre composition.* The relatively high type II muscle fibre composition (~60%) of the hamstrings has been postulated to be an architectural characteristic resulting in a higher risk of sustaining a strain injury. However, based on studies which have found relatively higher composition of type two muscle fibres in the vastus lateralis and yet, lower incidences of injury at the quadriceps, it is possible that the role of muscle fibre composition as a risk factor of injury has been overstated. Therefore, a more valid approach might be to compare architecture features of the muscles and understand how differences in this feature, rather muscle fibre type affect injury risk.

*Double-headed biceps femoris.* The unique structure of the hamstring muscles, especially that of the BF1h, which comprises two separately innervated heads, has been commonly accepted as a reason why the muscle site is especially prone to strain injuries. This
is due to the occurrence of uncoordinated contractions as a result of this unique architectural feature, which result in “instability” in the muscle during contractions (Zuluga et al., 1995).

From a cadaveric study, it has also been suggested that the combination of smaller physiological cross-sectional area and shorter fascicles in the BFsh compared to the BFlh, weakens the integrity of the BF and predisposes it to injury (Brockett et al., 2004). Longer fascicles permit greater muscle extensibility (Butterfield, 2010) and reduce the risk of excessive lengthening of the hamstrings during eccentric contractions (Thelen et al., 2005). However, the BFlh which undergoes the most lengthening during sprint-based activities has shorter fascicles compared to the BFsh and this may result in the BFlh being predisposed to repeated excessive lengthening and result in muscle damage. However, it is important to note that in the study by Brockett and colleagues, cadaveric measurements were taken on donors aged 66-88 years and this greatly reduces the generalizability of results given the expected atrophy of muscle structures.

*Proximal aponeurosis width.* Due to the typical occurrence of muscular strains at sites near the MTJ, the architecture of the muscle, as well as tendon, are likely to be important factors underlying injury risk. A recent study utilising 3-D modelling techniques to describe muscle architecture suggested that the width of BFlhd proximal aponeurosis might be a crucial architecture risk factor (Rehorn & Blemker, 2010). In addition, it has been established in a previous large-scale study that the size of the BFlh proximal aponeurosis varies between different people (Evangelidis, Massey, Pain & Folland, 2014); and individuals which present a smaller aponeurosis could be at higher risk of sustaining a HSI (Fiorentino et al., 2012).

However, it is challenging to measure proximal aponeurosis width without the use of MRI because there is no clear association to muscle strength or size (Evangelidis et al., 2014). Individuals with small and high aponeurosis areas (7.5 and 33.5 cm² respectively) were observed to have similar biceps femoris long head maximum anatomical cross-sectional

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areas (14.1 and 13.3 cm²) (Figure 2.4). A similar absence of a relationship was observed for both the isometric \( r = 0.28, P = 0.13 \) and knee flexion strength under eccentric contraction \( r = 0.24, P \geq 0.13 \) (Figure 2.5) (Evangelidis et al., 2014).

![Scatter plot illustrating biceps femoris long head proximal aponeurosis area and cross-sectional area for thirty participants.](Evangelidis et al., 2014)

**Cross-sectional area (CSA).** The CSA of the hamstring muscle tissue has also been highlighted as a likely risk factor of HSIs. Based on the results of previous studies utilising MRI to determine the CSA of the hamstring muscle tissue, there was weak evidence to suggest an association between CSA and injury risk. Verrall and colleagues (2006) found a significant relationship while in two other studies, no associations were established. (Gibbs et
al., 2004; Koulouris et al., 2007). Therefore, further investigation is warranted before a conclusive relationship between CSA of the hamstrings and injury risk could be determined.

Figure 2.5. Scatter plot illustrating hamstring isometric strength and BFh [A] ACAS, [B] proximal aponeurosis size and [C] ratio to St tendon CSA for thirty participants.

![Scatter plot](image)

(Evangelidis et al., 2014)

**Pelvic tilt.** Another risk factor might be the degree of anterior pelvic tilt since the ischial tuberosity (origin of the hamstrings), is found on the posterior aspect of the pelvis (Abebe, Moorman & Garrett, 2009). Therefore, excessive anterior pelvic tilt will result in the hamstrings being at being overstretched (Sherry & Besy, 2004) and some studies have
suggested that this may increase the risk of sustaining strain injuries (Woods, Hawkins & Maltby, 2004; Hennessey & Watson, 1993)

**Summary.** Although the previous studies have attempted to identify anatomical risk factors of HSI, the small sample size of most studies, coupled with the use of cadaveric measurements, limits the usefulness of results obtained in relation to assessing injury risk in athletes. Therefore, in order to have a complete understanding of the relationship between muscle anatomy and mechanism of HSI, more careful studies need to be conducted with regards to how muscle architecture variables are related to injury.

### 2.5.3.2 Functional.

*Hamstrings to quadriceps strength ratio.* Previous studies have provided strong evidence for strength asymmetries between the hamstrings and quadriceps as a risk factor for injury (Croisier et al., 2008; Yeung, Suen & Yeung, 2009). Traditionally, a method used by a large number of older studies to determine the relative strength of the hamstrings and quadriceps was to measure and compare peak torque of the hamstrings and quadriceps generated during concentric movements. This is widely known as the conventional H:Q ratio. However, the ratio of the measured hamstrings peak eccentric torque to quadriceps peak concentric torque is typically considered a more thorough and valid assessment of strength asymmetry (Aagard & Andersen, 1998); and this is termed the functional strength ratio. In a notable study by Croisier and colleagues (2002), it was found if only conventional rather than functional H:Q ratios were considered, one-fifth of individuals with a prior HSI would not have been positively identified.

In an earlier study of professional footballers evaluated over the course of preseason by Croisier and colleagues (2008), a low conventional (0.47) and functional (< 0.80) H: Q strength ratio was found to multiply the risk of sustaining a HSI by four times. In another
study of elite sprinters over the course of a racing season, it was found that individuals who had a conventional strength ratio of below 0.60 were 17 times more likely to sustain a HSI (Yeung, Suen & Yeung, 2009). However, in an earlier study, the strong associations were not present as Benell and colleagues (1998) found no relationship between both measures of conventional and functional strength ratios with injury risk.

In majority of studies examined, the focus has been on the strength asymmetry measured by an individual’s ability to generate peak torque. However, an important variable which is receiving more attention in being investigated as a risk factor of HSIs is the time required to generate peak torque. In a recent study, the functional H:Q strength ratio (0.17) was found to be lower than the conventional H:Q strength ratio (0.56) during the initial state of a muscular contraction (50ms from the start of muscle activation) (Hannah, Minshull, Smith & Folland, 2014). This suggests that the explosive phase of the sprint movement might be when individuals are most vulnerable to the onset of a HSI.

*Rate of torque development.* A study had found lower levels of EMG activity in a hamstring with a prior strain injury during maximum effort eccentric contractions at a testing velocity of 60 degrees/s (Sole, Milosavljevic, Nicholson & Sullivan, 2011). As the main role of the hamstrings is to rapidly decelerate the advancing thigh during the late to end swing phase of high-speed running movements (Thelen et al., 2005), optimal hamstring function during this portion of the gait cycle is important. Sub-optimal rates of force development might prevent the adequate development of torque necessary to decelerate the thigh (Heiderscheit et al., 2005).

In a study looking at the effect of a previous HSI on the EMG activity of the hamstrings during isokinetic dynamometry (Opar, Williams, Timmins, Dear & Shield, 2013), it was found that the previously injured hamstrings showed lower rates of torque.
development during slow eccentric contractions compared with the contralateral uninjured limb; with lower myoelectrical activity found at the biceps femoris. In the injured group, compared with the contralateral uninjured limb, rate of torque development was lower in the injured limb during 60 deg/s eccentric contractions at 50 ms (injured limb: 312.27 ± 191.78 N·ms⁻¹; uninjured limb: 518.54 ± 172.81 N·ms⁻¹, \( p = .008 \)) and 100 ms (injured limb: 280.03 ± 131.42 N·ms⁻¹; uninjured limb: 460.54 ± 152.94 N·ms⁻¹, \( p = .001 \)) after the onset of contraction (Figure 2.6). Therefore, a bilateral difference in the rate of torque development might be present in previously injured athletes that puts them at a greater risk of re-injury.

![Figure 2.6](image)

**Figure 2.6.** Comparisons between the injured and uninjured of previously-injured athletes' rate of torque development measured in the knee flexors,

(Opar et al., 2013)

The rate of torque development is closely related to musculotendinous properties such as muscle size, relative area of fast-twitch fibres, myosin heavy chain isoform composition

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and tendon stiffness (Bojsen-Moller, Magnusson, Rasmussen, Kjaer & Aagard, 2005; Hakkinen, Alen & Komi, 1985; Harridge et al., 1996). Therefore, the consideration of muscle architecture variables when assessing the rate of torque development is important; specifically, with the extent of EMG activity during the early phase of muscle contraction.

*Length-tension relationship.* It has been suggested that individuals with a greater knee angle at peak concentric knee flexion torque are at greater risk of sustaining HSI (Brockett et al., 2004). The hamstrings of these predisposed individuals would be expected to be activated to a larger extent on the descending limb of the length-tension relationship across a greater range of motion, which leaves them more prone to damage (Morgan, 1990).

It has also been found that athletes who have been previously injured showed peak knee flexion torque at a greater degrees of knee flexion on the injured side compared to the contralateral uninjured side (Figure 2.7, Opar et al., 2012; Brockett et al., 2004; Lee et al., 2009). Eccentric hamstring peak torque was found to be lower (26.2 N·m·kg⁻¹) and occurred at shorter hamstring lengths on the previously injured side (Lee et al., 2009).

A prospective study (Yeung, Suen & Yeung, 2009) conducted to investigate the relationship between angle of peak torque and possibility of sustaining a HSI in the near future in high-level sprinters found no association between the angle of peak knee flexor torque and subsequent HSI during the racing season.
Figure 2.7. Concentric knee flexor torque-joint angle relationship from a single elite male athlete tested at 60°/s.

(Opar et al., 2012)

At present, the handful of studies investigating the length-tension relationship of the hamstrings as a risk factor of injury are unable to provide any conclusive results. Therefore, more work is warranted in this area before conclusive relationships could be established between muscle length-tension and susceptibility to strain injuries.

Running biomechanics. In the only study identified which investigated the running biomechanics of individuals with a prior hamstring injury (Lee et al., 2009), it was found that peak hip flexion angle in late swing was significantly reduced (1.9°) in the previously injured limb (Figure 2.8). Other lower limb swing phase kinematics and kinetics were generally similar. Functional H: Q and eccentric hamstrings to concentric hip flexors ratios for peak torque and total work were reduced on the previously injured limb.
As most hamstring injuries occur during running, it is possible that certain characterisations of lower-limb joint kinematics predispose an individual to injury. However, to date, limited conclusive evidence exists regarding possible characterisations in individuals who have sustained a previous hamstrings injury. The aforementioned study by Lee and colleagues (2009) was important in establishing kinematic characterisations of previously-injured individuals. However, the researchers only investigated lower-limb kinematics during sub-maximal running. However, since muscle loading conditions increase with running speed...
(Thelen, Chumanov, Sherry & Heiderscheit, 2006), it will be useful to examine the biomechanics of injured and uninjured limbs under maximal sprint conditions found in many sports.

Although limited information exists relating sprinting kinematics to hamstring injuries, several attempts have been made to characterise maximum-effort over ground running (Sun et al., 2015; Kuitunen, Komi & Kyrolainen, 2002; Mann & Sprague, 1980). Sun and colleagues (2015) suggested that the large passive torques existed at both the knee and hip joints during the initial and late swing phases (Figure 2.9) of sprinting. As a result, the active muscle torque generated by the hamstrings which is necessary to counteract these passives torques might result in higher risk of HSI. This is consistent with a previous EMG study (Yu et al., 2008) which reported that peak activities of the medial and lateral hamstrings occurred during the initial stance and late swing phases.

Figure 2.9. [A] Averaged time-normalised graphs torque measured at hip and knee joints during the swing phase of running. [B] Illustration of forces during sprinting.

(Sun et al., 2015)
By understanding the loading condition on the hamstrings, especially the load production mechanism, preventive strategies can be developed to help reduce the high risk of HSI during high-speed running. However, it is also important to understand different individual responses to these conditions considering the differences in muscle architecture, visco-elastic property and function.

2.6 Hamstrings-specific strengthening exercises

The key words used in combination for the search were ‘hamstring(s)’, ‘exercise’, ‘interventions’, ‘training’, ‘strengthening’, ‘recommendations’, ‘eccentric’ and ‘nordic lower(s)’. A total of 77 relevant papers, dissertations/theses and abstracts were chosen from all return results and used in this thesis.

2.6.1 Common exercises. Common preventive strategies incorporating hamstrings conditioning included stretching, eccentric and concentric methods of strengthening, movement and posture corrections, neuromuscular therapeutic strategies, and general intervention programs (warm-up, aerobics, activity specific drills). The reported effectiveness of these various interventions was mixed. In some studies, there was no change in the incidence of HSIs reported with the use of stretching (Heiderscheit, Sherry, Silder, Chumanov & Thelenm 2010; Arnason, Andersen, Holme, Engebretsen & Bahr, 2008; Goldman & Jones, 2010). A number of studies recommended improvements in active range of motion through the use static stretching and strengthening programmes (Worrell & Perrin, 1992; Brooks, Fuller, Kemp & Reddin, 2006; Henderson, Barnes & Portas, 2010), or stretching while a muscle is fatigued (Verall, Slavotinek & Barnes 2005). Massage was found to be moderately effective while balance conditioning and various warm up/cool down protocols had weak supportive evidence, or inconclusive evidence, for the prevention of lower-limb injuries (Goldman &
Jones, 2010). Strengthening exercises reported varying levels of effectiveness based on the specificity of exercise being performed. A number of authors advocated for eccentric and concentric exercises for the hamstrings (Heiderscheit et al., 2010; Worrell & Perrin, 1992); while others recommended training drills specific to the sport being performed to reduce hamstring injury risk (Verall, Slavotinek & Barnes, 2005).

The exact mechanism underlying the results of from the above studies have been vague or under-explained. Few studies have specifically compared the difference in muscle activity levels across different hamstring exercises that are commonly used. In a comparison of three proprioceptive neuromuscular facilitation stretch techniques, the agonist contract-relax method was found to result in 65-119% more EMG activity than the static stretch and contract-relax techniques (Ferber, Osternig & Gravelle, 2002). In another study (Glenn, Delong & Gehlsen, 1999) investigating the differences in muscle activity across three hamstrings strengthening exercises (leg curl, stiff-leg deadlift and back squat movements), EMG data representing muscle activation suggested that the leg curl and single-leg deadlift were equally effective in strengthening the hamstrings. In these studies, the basis to choose the best exercise for hamstring strength involvement was based on peak EMG activity of the hamstring during each exercise. Although peak muscle activity appears to be a relevant variable for comparison, it should not be the only factor considered in deciding the efficacy of various exercises. Other factors such as the timing onset of activation and accompanying changes in muscle architecture should also be considered. Therefore, further studies are warranted to determine the suitable variables which allow for a valid comparison of exercise efficacy.

In general, there was little evidence from various randomised controlled trials to draw definitive conclusions about the efficacy of the above-mentioned interventions in preventing hamstring injuries. However, recent published literature suggests that eccentric strengthening
exercises appear to have some preventative effect on hamstring strain injuries. This will be reviewed in detail in the next section of this chapter.

2.6.2 Eccentric strengthening exercises. Eccentric training refers to the mechanism of the contraction of a muscle for decelerating or stabilising the movement of a load while both tendon and muscle are stretching or in a stretched state. The high forces that can be produced during eccentric contractions appear to be able to induce a more effective remodeling response when applied progressively and chronically (LaStayo et al., 2003). However, to date, the specific mechanisms underlying this process remains largely unknown.

Maffulli and Longo (2008) put forth three basic principles in the eccentric loading process which are (i) the lengthening of the tendon when it is pre-stretched results in less strain acting through the tendon while moving, (ii) tendon strength should undergo a gradual increase by progressively increasing load on the tendon and (iii) when the speed of a contraction is increased, larger forces would be generated.

It has been suggested that eccentric exercises result in the muscle tendon being exposed to a greater load compared to concentric exercises (Stanish, Rubinovich & Curwin, 1986). However, peak tendon forces during eccentric loading have been found to be similar to those during concentric loading (Rees, Lichtwark, Wolman & Wilson, 2008) and this suggests that other mechanisms may be responsible for the efficacy of eccentric exercises. Possible mechanisms include an increase in muscle fibroblast (cell responsible for structural integrity of connective tissues) activity (Rees, Lichtwark, Wolman & Wilson, 2008), collagen realignment (Peers & Lysens, 2005) and increase in the number of sarcomeres in series (Whitehead, Allen, Morgan & Proske, 1998).

Several experimental studies have been conducted investigating the efficacy of eccentric strengthening exercises targeting the hamstrings. In a study utilising a YoYo™
flywheel ergometer, Askling and colleagues (2003) examined the effects of pre-season
hamstrings strengthening among football players by utilising concentric and eccentric
overload exercises. It was found that the eccentric training group reported significantly lower
number of injuries compared to the control group. However, a significant limitation of the
study was the difficult in distinguishing between concentric and eccentric activation phases
during the exercise on the YoYo™ flywheel ergometer.

In two studies utilising isokinetic eccentric strengthening, positive effects relating to
injury reduction were reported. By utilising a training programme individualised to each
participant’s eccentric peak torque deficit, Croisier and colleagues (2002) reported zero
incidence of hamstring strains in male athletes during the first 12 months upon return to sport.
In a similar study with a nine-month follow-up period, no recurrent hamstring injuries were
also reported (Queiros Da Silva et al., 2005). However, these studies were prospective cohort
studies without a control group for comparison. In addition, the efficacy of eccentric training
alone cannot be fully evaluated as a mix of interventions were utilised. More recently, the
focus on eccentric training and practical need for exercises which are simpler to implement
(e.g. calisthenics), has resulted in the increase in popularity of ‘Nordic hamstring lowers’
exercises which will be reviewed in the next section of this chapter.

2.6.3 Nordic hamstring lowers. The Nordic hamstring lowers (NHL) protocol
(Figure 2.10) involves participants kneeling on a flat surface with an upright trunk position
that is perpendicular to the surface. The participants’ feet would be supported either under an
implement or with assistance from a partner. With the arms kept close to the chest, the
participant would lower his or her body forward towards the floor. This would continue until
the participants unable to hold the position, at which point he or she would relax and support
themselves with their arms to cushion their fall.
Nordic hamstring exercises, such as NHL, have been proven effective among football players. Using these exercises, elite football players from Norway and Iceland reported lower incidences of hamstring injuries (Arnason et al., 2008), maximal eccentric strength increases (Mjolsnes et al., 2004), and an improved ability of the hamstrings to progressively withstand loading (Brito et al., 2010). There was also a reported shift in peak hamstring torque to a more extended knee-joint angle position after NHL training (Clark, Bryant, Culgan & Hartley, 2005). Clarke and colleagues (2005) also postulated that since most HSIs occur while the hamstrings are undergoing eccentric contraction, the ability to generate more torque in an extended knee position may be effective in reducing the onset of muscle strains.

In one study (Brooks, Fuller, Kemp & Reddin, 2006) which compared the effectiveness of NHL, conventional strengthening and hamstrings stretching on reducing the incidence and severity of hamstring injuries, it was found that the participants in the intervention group which utilised an exercise regime comprising conventional strengthening and stretching with NHL reported significantly lower injuries (0.39 injuries/1000 playing hours) than in the strengthening group (1.1 injuries/1000 playing hours) and conventional strengthening and stretching group (0.59 injuries/1000 playing hours). In another
experimental study comparing the efficacy of NHL and stretching, incidence of HSIs reported in the eccentric strengthening group and stretching group were 4% and 13% respectively (Gabbe, Branson & Bennell, 2006).

The positive reductions in hamstring injury incidence reported seem to suggest that NHL is effective in contributing towards a protective effect from hamstring injuries. However, the exact mechanism underlying the improvements is unknown. Thus, it will be useful to conduct a study is conducted to assess muscle architecture and functional changes associated with improvements from NHL.

2.7 Muscle architecture, visco-elastic property and function assessment tools

Throughout this study, a variety of measures of hamstrings muscle architecture, visco-elastic property and function will be taken. The following sections review the current literature related to the validity and reliability of the assessment tools which are (i) dynamometry, (ii) ultrasonography, (iii) surface electromyography, (iv) myotonometer and (v) motion analysis.

2.7.1 Dynamometry. Dynamometry (Figure 2.11) has been widely considered as the ‘gold standard’ for the objective assessment of muscular strength due to its scope for allowing a detailed evaluation of an individual’s muscle function through a full range of motion by providing an equivalent resistant torque across different testing velocities (isokinetic dynamometry) or angles (isometric dynamometry). It is commonly used in research and clinical practice to assess the muscle function of the knee flexors and extensors as they are prime movers for several important functional activities.
The parameters that can be assessed about an isokinetic muscle movement using dynamometry include torque (Newton·metres), range of motion (degrees) and duration of muscle action (seconds). In the studies outlined in this proposal, both isokinetic and isometric dynamometry will be utilised to assess hamstrings muscle function through a variety of testing conditions highlighted in Chapter 3.

The measurement of muscle strength utilising isokinetic dynamometry can be described as the quantitative expression of a muscle’s peak torque generation at a specific velocity of contraction (Taylor & Fletcher, 2012). This form of testing has generally been found to be valid and reliable.

There is strong evidence for high between-test reliability scores performed using the same isokinetic dynamometer during testing (intra-machine reliability) (Feiring, Ellenbecker & Dercheid, 1990; Impellizzeri, Bizzini, Rampinini, Cereda & Maffiuletti, 2015; Li, Maffuli, Chan & Chan, 1996; Sile). The results of these findings suggest that researchers and
clinicians can have confidence in measurements to check a participant’s progress throughout a rehabilitation program if the same dynamometer is used throughout all tests. However, very few studies assessed the reliability of measurements between different isokinetic dynamometers (inter-machine reliability) with results reported being largely inconsistent (Bandy & McLaughlin, 1993; Cotte & Ferret, 2003; Keilani et al., 2007; Lund et al., 2005).

In a study comparing isokinetic knee extensor and flexor torque at 60, 180 and 240 degrees/s measured by Biodex 3 and Cybex 6000 dynamometers, the Cybex 6000 device showed significantly lower values than the Biodex 3 measurements (paired-t-test: all \( p < 0.0001 \)) (Keilani et al., 2007). On the other hand, Lund and colleagues (2005) found no difference in muscle strength measured between the Biodex 3 and Lido Active dynamometers for measures of both knee flexion and extension. Based on the few studies available, it is evident that present literature is not conclusive to suggest that inter-device measurements can be compared, hence, it is important to maintain the consistency of measurements by using the same testing device within a study.

One study (Impellizzeri, Bizzini, Rampinini, Cereda & Maffiuletti, 2007) which investigated the reliability of isokinetic hamstrings to quadriceps ratios at 60, 120, 180 and -60 degrees/s using the Humac NORM dynamometer (testing device used in this PhD study), found low (0.34) to moderate (0.87) relative reliability (intraclass correlation coefficient, ICC) for strength imbalance ratios. High ICC values (0.90-0.98) were reported for variables such as peak torque generated and average work done. This study established the reliability of the most commonly assessed strength imbalance ratios and of absolute isokinetic muscle strength assessed using the Humac NORM dynamometer.

Drouin and colleagues (2004) assessed the instrument (Biodex) validity by comparing measures of peak torque to a criterion reference value using theoretical calculations (Denegar
& Ball, 1993; Shrout et al., 1979) and found that isometric torque and position measurements were acceptable for both clinical and research purposes.

However, the measured (calculated by dynamometer) and the actual resultant moments at a joint in the same plane are only equivalent if the axis of rotation of the dynamometer is aligned correctly to the joint about the movement tested is conducted. It had been previously found that at the knee joint, the effect of knee movement to the dynamometer on the resultant moments could be considered negligible if the joint axis and the crank center were properly aligned before tested movement (Herzog, 1988). On the contrary, Kauffman and colleagues (1995) reported that the offset in values between crank and actual knee joint angle averaged 10–13% at isokinetic (60°/s and 180°/s) knee extensions. A similar discrepancy (3.5–7.3%) was reported during isometric testing (80–170°) in a more recent study (Arampatzis et al., 2004). This is possibly due to the compliance of the soft tissue around the tested joint resulting in muscle deformation (Kauffman et al., 1995).

Generally, based on the few existing recent studies, isokinetic and isometric dynamometry have been found to be able to provide valid and reliable results. However, there are limitations to dynamometry such as the knee joint and crank angle offset (Kauffman et al., 1995) which will be addressed subsequently in Preliminary Study 1 (Chapter 4).

2.7.2 Ultrasonography. Ultrasonography (Figure 2.12) has been considered to be a less expensive, more efficient and user-friendly imaging tool to assess muscle architecture variables in vivo than MRI (Lieber & Ward, 2011). It allows for the measurement of different muscle architecture variables such as fascicle length and pennation angle in various positions or during different activities (static or dynamic) (Kwah, Pinto, Diong & Herbert, 2013). Recent improvements in ultrasound technology such as the extended field-of-view imaging (Fornage, Atkinson, Nock & Jones, 2000) has also allowed observations of long muscle...
fascicles (e.g. hamstrings) under static conditions (Noorkoiv, Stavnsbo, Aagaard & Blazevich, 2010).

Figure 2.12. Typical ultrasound assessment set-up with measurements taken using a transducer probe placed over the surface of the muscle of interest.

(Source: www.tornhamstring.org)

A handful of studies have investigated the reliability of using ultrasonography in the measurement of muscle fascicle length and pennation angle. Comparatively, a smaller number of studies have examined the validity of these measurements of muscle architecture. This is due to the inherent difficulty in validating muscle architecture measurements which require a comparison with direct measurements in cadaveric muscle.

Only two studies identified utilised cadaveric data of fascicle length and pennation angle to validate ultrasound measurements. The data from these studies showed that the accuracy of measurements ranged from high to very high fascicle lengths: ICC = 0.77– 0.91; pennation angles: ICC = 0.88–0.97) (Benard, Becher, Harlaar, Huijing & Jaspers, 2009; Kawakami, Takashi & Fukunaga, 1993).
Reliability estimates of variables for muscles imaged in a relaxed state were generally high to very high for fascicle lengths (ICC= 0.74-0.99, r=0.96, CV = 0.0-6.8% and SEM = 0-19 mm) and ranged from moderate to high for pennation angles (ICC = 0.62–1.00, r = 0.87–0.95, CV = 0.0–8.5% and SEM =0.1–1.2°) (Alegre, Jumenez, Gonzalo-Orden, Martin-Acero & Aguado, 2006; Blazevich, Gill & Zhou, 2006; Brancaccio, Limongelli, D’Aponte, Narici & Maffulli, 2008; Mohagheghi et al., 2007; Padhiar, Al-Sayeagh, Chan, King & Maffulli, 2008; Staehli, Glatthorn, Casartelli & Maffiuletti, 2010). Similar reliability estimates were observed for muscles in a contacted state (fascicle length: ICC =0.62–0.99, CV = 0.0–8.3% and SEM = 1–17 mm; pennation angles: ICC = 0.51–1.00, CV = 0.0–8.3% and SEM = 0.9–1.2°) (Aggeloussis, Giannakou, Albracht & Arampatzis, 2010; Chleboun, Busic, Graham & Stuckey, 2007; Duclay, Martin, Duclay, Cometti & Pousson, 2009; Kurokawa, Fukunaga & Fukashiro, 2001; Mairet, Maiseti & Portero, 2006; Seiberl, Hahn, Kreuzpointner, Schwirtz & Gastmann, 2010).

When comparing ultrasound measures across at least two different sessions, reliability estimates of muscle fascicle length were generally moderate to very high (ICC = 0.62– 0.99, r = 0.93– 0.96, CV = 2.3–9.8%, SEM = 2–19 mm) while those of pennation angles were marginally lower but still fell within the same range of reliability (ICC = 0.51–1.00, r = 0.87–0.95, CV = 2.1–13.5%, SEM = 0.2–1.2°) (Aggeloussis et al., 2010; Alegre et al., 2006; Blazevich et al., 2006; Kim et al., 2010; Legerlotz, Smith & Hing, 2010; Maganaris, Baltzopoulos & Sargeant, 1998; Noorkoiv, Stavnsbo, Aagard & Blazevich, 2010; Staehli et al., 2010).

When measurements were calculated from the same ultrasound images over repeated imaging at the same muscle and site, reliability estimates for both fascicle lengths (ICC = 0.87– 0.99, CV = 0.0–8.3% and SEM = 0–8 mm) and pennation angles (ICC = 0.85–1.00,
CV = 0.0–8.3%, and SEM = 0.3–0.6°) ranged from high to very high (Aggeloussis et al., 2010; Blazevich et al., 2006; Chleboun et al., 2007; Fukunaga, Ichinose, Kawakami & Fukashiro, 1997; Kurokawa et al., 2001; Muramatsu, Muraoka, Kawakami, Shibayama & Fukunaga, 2002; Muraoka, Muramatsu, Kanehisa & Fukunaga, 1999; Padhiar et al., 2008).

Only 4 studies have inter-rater reliability of ultrasound measurements with estimates ranging from high to very high (fascicle lengths: ICC = 0.80–0.97 and r = 0.74; pennation angles: ICC = 0.80 and r = 0.76) (Brorsson, Nilsson, Hilliges, Sollerman & Aurell, 2008; Kim et al., 2010; Nororkoiv et al., 2010; Seiberl et al., 2010).

In general, ultrasound measurements of muscle fascicle lengths and pennation angles were reliable when muscles were imaged in both relaxed and contracted states, and when repeated between sessions, images and raters. Based on the limited studies investigating validity of ultrasound measurements, muscle fascicle length and pennation angle can be accurately determined from ultrasound images.

2.7.3 Surface electromyography. Surface EMG is a technique of assessing muscle activity in which electrodes are positioned on the skin overlying a muscle (Figure 2.13) to detect the electrical activity (Figure 2.14) of the muscle. It is commonly used to quantify both the magnitude and timing of muscle activation during different movements. The attractiveness of sEMG lies in its non-invasive nature. However, sEMG data can be variable and several studies have been conducted investigating the reliability of measurements obtained from this technique.

The reliability of sEMG measurements from isometric tasks is well established (Christ, Slaughter, Stillman, Cameron & Boileau, 1994; Kellis & Katis, 2008; McCarthy, Callaghan & Oldham, 2008; Sleivert & Wenger, 1994; Viitasalo & Komi, 1975). sEMG readings between isometric testing sessions has been found to be highly reliable for
quadriceps activation with a mean ICC of 0.99 and CV ranging from 5.3-7.2% (McCarthy et
al., 2008; Rainoldi, Bullock-Saxton, Cavarretta & Hogan, 2001). For the hamstrings, it has
been found to range from being moderately to highly reliable with ICC values ranging from
0.69-0.77 during a series of ramp isometric contractions (Kellis & Katis, 2008).

![Image of typical set-up of surface electromyography testing involving electrode placement on sites of interest.](Schulze et al., 2011)

**Figure 2.13.** Typical set-up of surface electromyography testing involving electrode placement on sites of interest.

![Sample of typical measurement data from sEMG indicating muscle activity level while performing voluntary isometric contractions.](Danner et al., 2015)

**Figure 2.14.** Sample of typical measurement data from sEMG indicating muscle activity level while performing voluntary isometric contractions.
Similarly, high reliabilities were observed for the quadriceps between trials of slow dynamic and ballistic movements with ICC values from 0.70-0.88 (Goodwin et al., 1999). However, the hamstrings showed poorer reliability between sessions of vertical jump tasks (ICC = 0.24 for the BF) (Goodwin et al., 1999). Within-session assessments of EMG data of lower-limb muscles during dynamic tasks such as vertical jumps, walking and squats have produced high reliability estimates with ICC ranging from 0.93-0.99 (Bolga & Uhl, 2007; Earl, Schmitz & Arnold, 2001; Kadaba et al., 1989; Knutson, Soderburg, Ballantyne & Clarke, 1994). However, the generalisability of these results is only limited to slower dynamic conditions with information on reliability of sEMG during faster dynamic tasks (e.g. sprinting) still lacking.

2.7.4 Myotonometry. The myotonometer is an electronic tissue compliance meter (Figure 2.15) that can be utilised to quantify the compliance of soft tissues in a body. It is commonly used to assess the changes in tissue compliance at various muscles after an intervention to determine the effect of a treatment.

To date, majority of studies investigating the reliability and validity of the myotonometer has been limited to assessments of the upper limbs. By comparing myotonometer measurements against those obtained from the Modified Ashworth Scale (MAS), assessments of muscle tone of the biceps brachii showed moderate to high correlation ($r = 0.65-0.81$) in individuals with upper motoneuron involvement (Lenard, Stephens & Stroppel, 2001). Similar validation of plantarflexor tone was demonstrated in stroke survivors (Rydahl & Brouwer, 2007).
Figure 2.15. Use of myotonometer to measure muscle visco-elastic properties.

(Ligia et al., 2012)

In an intra- and inter-rater reliability study (Aarrestad et al., 2004) of the Myotonometer, the device demonstrated high to very high intra- and inter-rater reliabilities for measurements of the biceps brachii and medial gastrocnemius muscle tone of children with spastic-type cerebral palsy. Intra-rater reliabilities ranged from 0.82-0.99 (biceps brachii) and 0.88-0.99 (medial gastrocnemius). Inter-rater reliabilities ranged from 0.74-0.99 (biceps brachii) and 0.84-0.99 (medial gastrocnemius muscles). Repeatability coefficients indicated a 98% level of agreement between raters across all conditions. In a separate study of both children with and without cerebral palsy, similar intra- and inter-reliability values of the rectus femoris muscle tone were observed (Lidstrom, Ahlsten, Hirschfeld & Norrlin, 2009).

In the measurement of BF muscle stiffness, the use of the myotonometer has been found to have high inter-day reliability (0.92) and was suggested to be general reliable for clinical muscle assessment (Lam, Mok, Lee & Chen, 2015). However, in another study which investigated validity and reliability of the myotonometer on the active hamstrings muscle tone (Pamukoff, Bell, Ryan & Blackburn, 2016), it was observed to demonstrate good intra-
session (ICC = 0.807) and inter-rater reliability (ICC = 0.830), and moderate inter-session reliability (ICC = 0.693). However, the myotonometer did not provide a valid measurement of the musculotendinous stiffness when compared against the damped oscillatory technique (r = 0.346, p = 0.061).

Further investigation into the validity of the myotonometer as a measurement of muscle tone is warranted. However, the established reliability of the myotonometer indicates that its use to provide a relative comparison of muscle tone between individuals and across conditions can be justified.

2.7.5 Motion analysis. The ‘gold standard’ for running and dynamic movement analyses for both clinical and research purposes is three-dimensional (3D) motion-capture. However, the utilisation of 3D analysis results in several significant financial, spatial and temporal costs (Maykut, Taylor-Haas, Paterno, DiCesare & Ford, 2015). Therefore, there is a need for a reliable and valid alternative. The most common alternative is two-dimensional (2D) video analysis which involves the use of standard commercially available cameras and software to conduct kinematic analyses of dynamic movements. The common data analysis process involves automatic tracking of body markers or manual digitisation of these markers by the rater.

Several studies have been conducted to evaluate the validity and reliability of 2D software during dynamic movements such as jumping and running (McLean et al., 2005; Mclay & Manal, 1998; Hollman et al., 2009; Munro, Herrington & Carolan, 2012; Olson, Chebny, Wilson, Kernozek & Straker, 2011; Willson & Davis, 2008; Norris & Olson, 2011). However, most of these studies have primarily focused on assessment of frontal plane kinematics. The results of a large proportion of these studies have found a high correlation between both 2-D and 3-D motion analyses of peak knee angles measured in the frontal plane.
(McClen et al., 2005), very high to excellent intra-rater and within-day inter-trial reliability for hip adduction (Hollman et al., 2009) and knee valgus (Herrington & Munro, 2010); and moderate to high between-day test-retest reliability for knee valgus (Miller & Callister, 2009).

Much lesser studies have looked at sagittal plane kinematics. In a study (Gribble, Hertel, Denegar & Buckley, 2005) examining sagittal plane kinematics at both the hip and knee during a single leg squat, the authors reported moderate validity for 2D analyses based on a measurement error of less than four degrees for the knee and ankle; and less than 11 degrees for the hip. A high test-retest reliability was also observed (ICC = 0.76-0.89). In another study (Norris & Olson, 2011), both intra-rater and inter-rater reliability values of hip and knee flexion angles were excellent (ICC ≥ 0.91). ICCs for test-retest reliability were observed for hip (0.79) and knee flexion (0.91). Validation of measures against goniometric assessment also demonstrated high correlations (r ≥ 0.95); and non-significant differences between both 2D and goniometric measures of sagittal plane hip and knee motion.

In general, 2D motion analysis can be considered a suitable alternative to 3D motion analysis due to its high reliability and validity. The financial and temporal savings from utilising 2D motion analysis over 3D analysis could be translated into a more effective testing protocol (especially for studies involving different and multiple assessments) without a compromise in data quality.

2.8 Summary

In this chapter, a review of literature on HSI was presented. Although there has been substantial work done in the area of understanding the etiology of HSI, the multi-factorial and complex nature of the injury means that further investigation is still warranted to fully understand the etiology of injury. Different architecture measures of the hamstrings (BF
proximal aponeurosis width and CSA) have been proposed as possible risk factors of injury, however, the small number of these studies with contrasting findings means that conclusive evidence relating muscle architecture to hamstrings injury risk cannot be established. Thus, further research is warranted to address this research gap.

Although a large number of preventive exercises have been studied, the wide-ranging results suggest that individual factors might influence the response to these interventions. There is also a lack of systematic studies specifically comparing outcome variables from a range of preventive exercises. Therefore, the limited scientific information evaluating the efficacy of various hamstrings strengthening exercises also warrants the need for a systematic evaluation of suitable training programmes. The increased popularity of NHL due to its ease of application and suggested effectiveness requires the need for a detailed investigation into its underlying mechanisms. The results of the review also suggest that the range of muscle architecture, visco-elastic and function measurement tools (ultrasound, myotonometer, electromyography, 2D motion analysis and dynamometry) used in this study are generally valid and very reliable.
Chapter 3: Hamstring Structural and Functional Differences Between Previously-injured and -uninjured Athletes

3.1 Introduction

Hamstring strain injuries (HSI) is a highly prevalent injury among sports that involve repetitive instances of movements such as high-speed running and turning actions (e.g. football and rugby). During the English Football Association’s comprehensive two-year record of injuries sustained by football players in the country’s domestic league, it was found to be the most common injury reported (Woods et al., 2004). A study of Australian Football League players also found it to be responsible for 15% of all injuries reported across a season (Orchard & Seward, 2002). The substantial rehabilitative period associated with HSIs translates into extended time loss in sport that affects players at both recreational and elite levels. These costs highlight the need for evidence-based HSI prevention strategies.

To date, there has been a substantial amount of research directed towards understanding the efficacy of various prophylactic exercises such as the Nordic hamstring lowers (Petersen et al., 2011; van der Horst et al., 2015). A large body of literature suggests that exercises which eccentrically strengthen the biceps femoris (BF) may prove effective in reducing the risk of HSIs (Askling, Karlsson & Thorstensson, 2003; Seagrave et al., 2014). The skewed focus of many of these training programmes which specifically target strengthening the BF could be attributed to the fact that almost 80% of HSIs involve the BF (Verrall et al., 2003; Silder et al., 2008). As a consequence, few studies have investigated the role of the similarly superficial and voluminous semitendinosus (ST) in the occurrence of HSIs. Therefore, there is a limited understanding of the characteristics of the ST, specifically its structure, as a possible risk factor of HSIs. Insight into the risk factors of HSIs can only be
complete with a consideration of both the structural and functional characteristics of the BF and ST.

Several studies have investigated the functional characteristics associated with a previously injured hamstring. Deficits in eccentric knee flexor strength, rate of torque development and changes in the angle of peak torque generation have been found in individuals with a previous HSI. The change in the angle of peak torque being generated at shorter muscle lengths has been suggested to be a result of shorter muscle fascicles (resulting in lesser in-series sarcomeres). However, there is little evidence to suggest that shorter fascicles are an architectural feature of previously injured hamstrings; either as an intrinsic risk factor or as a consequence of injury. To date, only one retrospective study has found shorter fascicles and larger pennation angles in the biceps femoris long head (BFlh) to be associated with previously injured hamstrings (Timmins, Shield, Williams, Lorenzen & Opar, 2015). Further evidence of this association is important before future studies can establish if shortened fascicles play a role in the underlying mechanisms causing HSIs.

Muscle architecture is defined as the arrangement of muscle fibres and the understanding of its characteristics plays an important role in biomechanical studies of the muscular system (Lieber, 2010). Advancements in medical imaging technology have made it possible to characterise muscle architecture through relatively inexpensive means. Two-dimensional (2-D) ultrasonography is one such method commonly utilised by researchers to assess muscle architecture in-vivo (Blazevich, 2006; de Oliveira, Carneiro & de Oliveira, 2016). 2-D ultrasound is able to provide information about several muscle architecture parameters such as muscle thickness, pennation angle and fascicle length. In the biceps femoris long head and semitendinosus, these parameters have been found to present good reliability and repeatability in the assessment of muscle architecture (Timmins et al., 2015; de Oliveira et al., 2016).
Besides muscle architecture, the visco-elastic properties of the hamstrings have been postulated as a risk factor of HSIs. It has been found that individuals with a history of HSI exhibit deficits in hamstring flexibility when compared to a control group (Brockett, Morgan & Proske, 2004); and poor hamstring flexibility is strongly associated with greater hamstring stiffness (Blackburn, Riemann, Padua & Guskiewicz, 2004). This could be attributed to lower muscular stiffness as the hamstrings allows the musculotendinous unit to lengthen with lesser tensile forces as compared to a stiffer muscle; resulting in an association between hamstring stiffness and the onset of a HSI (Watsford et al., 2010).

Methods of measuring stiffness include utilising the Ashworth Scale (Damiano, 2002), Myometer (Zinder & Padua, 2011), the damped oscillation technique (McNair, 1992), and the Myotonometer (Leonard et al. 2003; Aarrestad, Williams, Fehrre, Mikhailenok & Leonard, 2004). Of which, myotonometry (MMT) has become increasingly popular due to its ease of use as an on-field measurement tool for coaches. In the measurement of biceps femoris (BF) stiffness, it has been found to have high inter-day reliability and was suggested to be generally reliable for clinical muscle assessment (Lam, Mok, Lee & Chen, 2015).

Although the use of 2-D ultrasonography and MMT have become increasingly popular methods of assessing hamstrings muscle architecture and visco-elastic properties respectively, most of the data reported have been measured on the biceps femoris (Ditroilo, Hunter, Haslam & De Vito, 2011; Timmins et al., 2015). Moreover, to the author’s knowledge, there is no study which has investigated both muscle architecture and visco-elastic properties of both the BF and ST.

As most HSIs occur during high-speed running (Brooks et al., 2006), it is possible that certain characterisations of lower-limb joint kinematics predispose an individual to injury. However, to date, limited conclusive evidence exists regarding possible characterisations in individuals who have sustained a previous hamstrings injury. In an earlier
study (Lee, Reid, Elliott & Lloyd, 2009) which investigated the sprinting biomechanics of individuals with a prior hamstring injury, it was found that peak hip flexion angle in late swing was significantly reduced (1.9°) in the previously injured limb while other lower limb swing phase kinematics and kinetics were generally similar. Beyond these differences, there is limited understanding of the characteristics of muscle activation during sprinting and how they are coupled with differences in sprinting biomechanics, especially during the late swing phase where the onset of HSI tends to occur (Heiderscheit et al., 2005; Schache, Wriglet, Baker & Pandy, 2009).

Therefore, the purposes of this study were to first determine the test-retest reliability of 2-D ultrasound and MTT measures of muscle architecture (muscle thickness, pennation angle and fascicle length) and visco-elastic properties (stiffness, oscillation frequency and decrement). Subsequently, these measures were used to determine differences in muscle architecture and visco-elastic properties between previously-injured and -uninjured hamstrings. Another aim of this study was to investigate the functional differences of the hamstrings during sprinting by looking at kinematic and muscle activation measures. It is hypothesised that the previously injured hamstrings will exhibit shorter fascicles, larger pennation angle and appear stiffer when compared to the contralateral uninjured muscle and the control group. It is also expected that there would be strength deficits in functional measures of strength in the previously-injured hamstring. Running biomechanics and muscle activation characteristics would also be expected to be different between both limbs.

3.2 Methods

3.2.1 Participants. Fifteen male athletes from sprint-based sports (e.g. sprinting, football, hockey and frisbee etc.), with training commitments of at least 3 times per week were recruited for this study. Participant characteristics are shown in Table 3.1. Ten of these
participants with no prior HSI in the 18 months leading up to the start of the study formed the control group while five athletes with a self-reported unilateral BF strain injury history (within the last 18 months) formed the previously-injured group. HSI was defined as a sharp pain in the posterior aspect of the thigh that caused immediate termination of ongoing exercise (Opar et al., 2015); and all five previously-injured athletes reported the pain to be on the lateral side of the posterior thigh. Participants in the previously-injured group had returned to training at their pre-injury intensity prior to the start of the study. The control group also served as the test-retest group for measures of muscle architecture and visco-elastic properties. All participants provided written informed consent undertaken at the National Institute of Education, Nanyang Technological University, Singapore. Ethical approval for the study was granted by the Institutional Review Board of Nanyang Technological University, Singapore (Appendix 1).

| Table 3.1. Participant characteristics of male athletes from sprint-based sports. |
|---------------------------------|------------------|------------------|------------------|
| Age [years] | Previously uninjured (n=10) | Previously injured (n=5) | Total (n=15) |
| 23.2 (2.1) | 22.8 (1.9) | 23.1 (2.1) |
| Height [m] | 1.75 (0.32) | 1.73 (0.18) | 1.74 (0.35) |
| Body mass [kg] | 69.5 (3.2) | 67.0 (2.9) | 68.7 (3.3) |

3.2.2 Experimental design. Control group participants reported to the laboratory on two separate occasions spaced at least seven days apart. Participants in the previously-injured group reported for a single measurement session. All participants reported for their sessions at 08:30 AM. They were instructed to refrain from excessive physical exertion for 48 hours prior to the start of the measurement session. Structural measurements (muscle architecture and visco-elastic properties) of the hamstrings were first taken for all participants. Participants were then instructed to perform a self-selected warm for up to a period of 15 minutes before functional testing began.
3.2.3 **Hamstrings architecture assessment.** During the measurement session, the participant was instructed to lay prone on a bed with his feet hanging off the edge. A cushion was used for support under the participant’s chest. (Figure 3.1) Ultrasound images were taken along the longitudinal axis of the muscle belly using a two-dimensional, B-mode ultrasound (frequency = 12 MHz, depth = 8 cm, field of view = 14 - 47 mm; GE Healthcare Vivid-i, Wauwatosa, WI). Scans were taken at the mid-point between the ischial tuberosity and the knee joint fold, along the line of both the BF and ST (Timmins et al, 2014; Figure 3.2). At least five clear images were taken at each site for both legs. The linear array ultrasound probe was placed on the skin (lubricated by a layer of gel) over the site to be scanned. Care was taken to align the probe longitudinally and perpendicular to the surface of the posterior thigh. Minimal pressure was used to stabilise the probe on the skin to reduce its influence on the accuracy of measurement results (Klimstra et al., 2007).

![Figure 3.1. Participant in prone position on bed during ultrasound measurement.](image)

All images were exported and analysed offline using Kinovea software (Kinovea 0.8.15, Kinovea), which has been found to be a reliable (intra-rater ICC, >0.79) and valid measurement tool for angular and linear measurements (Puig-Divi et al., 2019). Methods of measurement for muscle architecture properties are shown in Figure 3.3. Muscle thickness (MT) was defined as the perpendicular distance from the deeper aponeurosis to the superficial aponeurosis. A fascicle was marked out on the image and the pennation angle
(PA) was defined as the average of angles formed between this fascicle with the superficial and deeper aponeuroses. Fascicle length (FL) was defined as the length of one complete fascicle. When the fascicle could not be fully seen, fascicle and aponeuroses lines were extrapolated to obtain a measurement. For both pennation angle and fascicle length, five fascicles were measured on the same image to obtain an average measurement.

![Diagram](image)

**Figure 3.2.** Measurement sites on biceps femoris (BF) and semitendinosus (ST)

**Figure 3.3.** Muscle architecture variables measured on ultrasound images.
3.2.4 Hamstrings visco-elastic property assessment. Visco-elastic properties (oscillation frequency, decrement and stiffness) were measured using a myotonometer (1 second interval; MyotonPRO, Myoton AS). Five measurements were taken at the same site (50% of posterior thigh length from ischial tuberosity to lateral (BF) and medial (ST) tibial epicondyle) on the BF and ST of both limbs in a relaxed state while lying in a prone position (Kong, Chua, Kawabata, Burns & Cai, 2018) (Figure 3.4).

![Figure 3.4. Use of handheld myotonometer to measure muscle visco-elastic property.](image)

3.2.5 Strength testing. Hamstrings isometric and isovelocity strength were measured with the participant sat in an upright position on an isokinetic dynamometer (HUMAC NORM Isokinetic Extremity System, Computer Sports Medicine Inc.) with a machine-set hip flexion angle of 100° (Figure 3.5). Alignment between the participant’s knee-joint center and crank center was undertaken while the muscle was contracting during knee-flexion at a mid-range angle (approximately 135°). Three separate fastening straps were used to minimise excessive lower-limb and trunk movement. They were positioned (i) slightly above the knee, (ii) at the proximal end of the femur and (iii) around the waist. Isometric strength during knee
flexion was measured across six different knee-joint angles (90°, 105°, 120°, 135°, 150° and 165°) (Alonso, McHugh, Mullaney & Tyler, 2009).

![Setup for isokinetic and isovelocity strength testing.](image)

In order to obtain measurements of the actual knee joint angle, two video cameras (120 Hz) were placed on the medial and lateral side of the tested knee to obtain sagittal views of the knee extension and flexion movement. Based on the sagittal view recordings of both the medial and lateral sides of the tested knee, the angle formed between the medial (Θ₁) (Figure 3.6) and lateral markers (Θ₂) (Figure B) with the horizontal could be determined. The actual knee joint angle was calculated by subtracting the total of these two angles from 360 degrees. Actual knee angle was calculated across six testing positions. Gravity corrected peak torque data was obtained from the software provided on the dynamometer. The sequence of testing angles was randomised between participants. Each participant performed two maximum efforts (lasting 2-3 seconds) at each angle. For isovelocity strength testing, participants performed two sets of three concentric/eccentric knee flexion cycles at 60°/s and 240°/s (Brockett et al., 2004). Hamstrings activity was recorded simultaneously during all testing through electromyography (EMG) at a sampling rate of 1500 Hz using a wireless
system (Myosystem 1400, Noraxon, Arizona). Electrode placement sites at the BF and ST were the same sites where ultrasound and MTT measurements were taken.

![Image of measurement setup](image-url)

**Figure 3.6.** (A) Angle formed between the medial markers and the horizontal ($\theta_1$); (b) angle formed between the lateral markers and the horizontal ($\theta_2$). Actual knee angle = $360^\circ - \theta_1 \cdot \theta_2$.

All data were exported and analysed offline using Spike 2 (CED Ltd., Cambridge, UK). The data from the torque output was low-pass filtered (Butterworth, 4th-order) utilising a cut-off frequency of 12 Hz. For analysing isometric strength, the peak torque (PT) generated at each angle across all efforts was selected for analysis. EMG signals were band-pass filtered between 20 to 450 Hz and subsequently root mean squared (RMS). The mean EMG value over a 500 ms window (250 ms before and after the instance of PT) was
calculated for each knee-joint angle position. The best concentric and eccentric efforts during isovelocity tasks were identified to obtain values of PT and angle of PT occurrence.

**3.2.6 Sprint biomechanics.** Participants performed five maximal effort sprints over a distance of 35 metres (Figure 3.7). Similarly, hamstrings activity (BT and ST) was recorded simultaneously during all efforts through electromyography (EMG) at a sampling rate of 1500 Hz using a wireless system (Myosystem 1400, Noraxon, Arizona). Reflective markers were placed on the lateral malleolus, greater trochanter of femur, lateral femoral condyle and shoulder acromion on both sides of the participant’s body (Clark, Barnes, Holton, Summers & Stratton, 2016) (Figure 3.8). Participants wore a sleeveless vest and a standard pair of fitting tights to ensure minimal movement of the markers during the sprinting motion. Videos in the sagittal plane were recorded at 240 Hz over the last seven metres of the sprinting task. Knee and hip joint kinematics were analysed offline using Vicon Peak Motus software (Vicon Motion Systems, Inc., Centennial, CO).

![Figure 3.7. Participant performing maximal sprint over 35 metres.](image-url)
The gait cycle was defined as the instance of first right foot strike to the next right foot strike. The gait cycle was further divided into four phases which were (i) **stance phase**: from footstrike to toeoff, (ii) **early swing phase**: from toeoff to maximum knee flexion, (iii) **middle swing phase**: from maximum knee flexion to maximal hip flexion and (iv) **late swing phase**: from maximum hip flexion to the subsequent foot strike. (Higashihara, Ono, Kubota, Okuwaki & Fukubayashi, 2010).

### 3.2.7 Statistical analysis

All statistical analyses were conducted with SPSS Version 24.0 (IBM Corporation, Chicago, IL). For test-retest reliability, descriptive statistics of architectural and visco-elastic properties of the BF and ST of both limbs in the control group were determined. Intraclass correlation coefficient (ICC), standard error of measurement (SEM) and minimum detectable change (MDC) at 95% confidence interval were subsequently calculated. MDC was calculated as $\text{SEM} \times 1.96 \times \sqrt{2}$. Based on previous quantitative reliability studies (Watsford et al., 2010), it was subjectively determined that an ICC $Q 0.90$ was regarded as high, between 0.80 and 0.89 was moderate, and less than 0.79 was poor. T-tests were used to compare structural and functional property differences.
between limbs in the control group, between contralateral limbs in the previously-injured group and between the mean of limbs in the control group and the previously-injured limb in the previously-injured group. Significance was set at \( P < 0.05 \), and where appropriate, Cohen’s \( d \) was reported to represent the effect size of comparisons, with the levels of effect being classed as small (\( d = 0.20 \)), medium (\( d = 0.50 \)), or large (\( d = 0.80 \)) as recommended by Cohen (1988). Due to the small sample size in the previously injured group (\( n = 4 \)), no inferential statistics were interpreted; and differences were evaluated using effect size (Cohen’s \( d \)). Comparisons were made between the control limb (CL, mean of both limbs in previously-injured group), injured limb (IL, injured limb in previously-injured group) and uninjured limb (UL, uninjured contralateral limb in previously-injured group).

3.3 Results

3.3.1 Inter-session reliability. Table 3.2 shows the muscle architecture and visco-elastic measurements values of the control group over the two testing sessions. All muscle architecture variables for both BF and ST in both limbs exhibited generally high reliability between sessions (Table A). ICC values were above 0.94 for all muscle architecture variables measured on the BF in both limbs. For the ST, ICC values were high for both pennation angle (\( \geq 0.92 \)) and fascicle length (\( \geq 0.95 \)) in both limbs while ICCs for muscle thickness ranged from moderate (left, 0.89) to high (right, 0.93). For muscle visco-elastic properties, reliability measures of stiffness and decrement in the BF of both legs were high (\( \geq 0.90 \)) with poor reliability between sessions in the measurement of oscillation frequency.

3.3.2 Control group inter-limb architecture and visco-elastic properties. There were no significant differences between the left and right limb in measurements of both muscle architecture (Table 3.3) and visco-elastic properties (Table 3.4) taken during the first measurement session. Based on this similarity between limbs for muscle structure properties,
a mean value of both limbs for muscle architecture and visco-elastic variables was calculated for participants in the control group.

**Table 3.2.** Descriptive statistics (mean ± standard deviation) and test-retest reliability data from the control group (n=10) for muscle architecture and visco-elastic properties of biceps femoris and semitendinosus.

<table>
<thead>
<tr>
<th></th>
<th>Session 1</th>
<th>Session 2</th>
<th>ICC Mean (95% CI)</th>
<th>SEM</th>
<th>MDC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Architecture</strong></td>
<td></td>
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<tr>
<td><strong>Biceps femoris</strong></td>
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<tr>
<td>Right leg</td>
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<tr>
<td>MT [cm]</td>
<td>2.30 ± 0.33</td>
<td>2.26 ± 0.33</td>
<td>0.97 (0.86–0.99)</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>PA [°]</td>
<td>16.9 ± 2.8</td>
<td>17.1 ± 2.7</td>
<td>0.96 (0.86–0.99)</td>
<td>0.56</td>
<td>1.55</td>
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<tr>
<td>FL [cm]</td>
<td>8.90 ± 1.06</td>
<td>9.02 ± 0.86</td>
<td>0.95 (0.80–0.99)</td>
<td>0.24</td>
<td>0.66</td>
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<tr>
<td>Left leg</td>
<td></td>
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<tr>
<td>MT [cm]</td>
<td>2.24 ± 0.25</td>
<td>2.25 ± 0.19</td>
<td>0.95 (0.78–0.99)</td>
<td>0.06</td>
<td>0.15</td>
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<tr>
<td>PA [°]</td>
<td>16.4 ± 2.6</td>
<td>16.6 ± 2.3</td>
<td>0.96 (0.85–0.99)</td>
<td>0.52</td>
<td>1.44</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>8.75 ± 1.15</td>
<td>8.80 ± 1.10</td>
<td>0.98 (0.92–1.00)</td>
<td>0.16</td>
<td>0.45</td>
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<tr>
<td><strong>Semitendinosus</strong></td>
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<td>Right leg</td>
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<tr>
<td>MT [cm]</td>
<td>2.31 ± 0.28</td>
<td>2.27 ± 0.22</td>
<td>0.93 (0.72–0.98)</td>
<td>0.07</td>
<td>0.21</td>
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<tr>
<td>PA [°]</td>
<td>14.4 ± 3.2</td>
<td>14.0 ± 2.2</td>
<td>0.96 (0.84–0.99)</td>
<td>0.64</td>
<td>1.77</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>10.05 ± 0.48</td>
<td>10.11 ± 0.56</td>
<td>0.95 (0.78–0.99)</td>
<td>0.11</td>
<td>0.30</td>
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<tr>
<td>Left leg</td>
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<td></td>
</tr>
<tr>
<td>MT [cm]</td>
<td>2.22 ± 0.26</td>
<td>2.24 ± 0.20</td>
<td>0.89 (0.57–0.97)</td>
<td>0.09</td>
<td>0.24</td>
</tr>
<tr>
<td>PA [°]</td>
<td>14.1 ± 2.6</td>
<td>13.3 ± 1.9</td>
<td>0.92 (0.69–0.98)</td>
<td>0.74</td>
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<tr>
<td>FL [cm]</td>
<td>10.33 ± 0.68</td>
<td>10.27 ± 0.48</td>
<td>0.95 (0.81–0.99)</td>
<td>0.15</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Visco-elastic property</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Biceps femoris</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>263.7 ± 51.2</td>
<td>258.3 ± 49.5</td>
<td>0.93 (0.72–0.98)</td>
<td>13.54</td>
<td>37.55</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.3 ± 1.9</td>
<td>16.1 ± 2.7</td>
<td>0.77 (0.09–0.94)</td>
<td>0.91</td>
<td>2.53</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.66 ± 0.30</td>
<td>1.55 ± 0.23</td>
<td>0.94 (0.75–0.99)</td>
<td>0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>Left leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>255.6 ± 39.5</td>
<td>253.7 ± 28.9</td>
<td>0.91 (0.64–0.98)</td>
<td>11.85</td>
<td>32.85</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.6 ± 1.2</td>
<td>17.4 ± 2.4</td>
<td>0.51 (-0.97–0.88)</td>
<td>0.84</td>
<td>2.33</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.69 ± 0.16</td>
<td>1.68 ± 0.11</td>
<td>0.91 (0.65–0.98)</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Semitendinosus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>231.9 ± 19.3</td>
<td>232.2 ± 15.2</td>
<td>0.77 (0.07–0.94)</td>
<td>9.26</td>
<td>25.66</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.7 ± 1.2</td>
<td>17.9 ± 1.1</td>
<td>0.72 (-0.11–0.93)</td>
<td>0.63</td>
<td>1.76</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.73 ± 0.08</td>
<td>1.74 ± 0.11</td>
<td>0.65 (-0.40–0.91)</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>Left leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>236.6 ± 14.8</td>
<td>241.9 ± 20.0</td>
<td>0.84 (0.36–0.96)</td>
<td>5.92</td>
<td>16.41</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>17.8 ± 1.9</td>
<td>17.3 ± 1.5</td>
<td>0.85 (0.40–0.96)</td>
<td>0.74</td>
<td>2.04</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.68 ± 0.16</td>
<td>1.70 ± 0.12</td>
<td>0.91 (0.62–0.98)</td>
<td>0.05</td>
<td>0.13</td>
</tr>
</tbody>
</table>

MT—muscle thickness; PA—pennation angle; FL—fascicle length; CI—confidence interval; ICC—intraclass correlation; SEM—standard error of measurement; MDC—minimum detectable change at 95% CI.
### Table 3.3: Muscle architecture properties of both limbs in the control group during the first measurement session.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
<th>p-value</th>
<th>Mean difference (95% CI)</th>
<th>Effect size (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT [cm]</td>
<td>2.30 ± 0.33</td>
<td>2.24 ± 0.25</td>
<td>.259</td>
<td>0.06 (-0.05–0.16)</td>
<td>0.20</td>
</tr>
<tr>
<td>PA [°]</td>
<td>16.9 ± 2.8</td>
<td>16.4 ± 2.6</td>
<td>.516</td>
<td>0.55 (-1.29–2.39)</td>
<td>0.19</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>8.90 ± 1.06</td>
<td>8.75 ± 1.15</td>
<td>.370</td>
<td>0.14 (-0.20–0.49)</td>
<td>0.14</td>
</tr>
<tr>
<td>MT [cm]</td>
<td>2.31 ± 0.28</td>
<td>2.22 ± 0.26</td>
<td>.055</td>
<td>0.09 (-0.00–0.18)</td>
<td>0.33</td>
</tr>
<tr>
<td>PA [°]</td>
<td>14.4 ± 3.2</td>
<td>14.1 ± 2.6</td>
<td>.717</td>
<td>0.31 (-1.58–2.20)</td>
<td>0.10</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>10.05 ± 0.48</td>
<td>10.33 ± 0.68</td>
<td>.068</td>
<td>-0.29 (-0.60–0.03)</td>
<td>0.29</td>
</tr>
</tbody>
</table>

### Table 3.4: Visco-elastic properties of both limbs in the control group during the first measurement session.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
<th>p-value</th>
<th>Mean difference (95% CI)</th>
<th>Effect size (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>263.7 ± 51.2</td>
<td>255.6 ± 39.5</td>
<td>.356</td>
<td>8.1 (-10.7–26.9)</td>
<td>0.18</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.3 ± 1.9</td>
<td>18.6 ± 1.2</td>
<td>.527</td>
<td>-0.3 (-1.4–0.8)</td>
<td>0.19</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.66 ± 0.30</td>
<td>1.69 ± 0.16</td>
<td>.557</td>
<td>-0.04 (-0.19–0.11)</td>
<td>0.12</td>
</tr>
<tr>
<td>ST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>231.9 ± 19.3</td>
<td>236.6 ± 14.8</td>
<td>.343</td>
<td>-4.7 (-15.3–5.9)</td>
<td>0.27</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.7 ± 1.2</td>
<td>17.8 ± 1.9</td>
<td>.216</td>
<td>0.91 (-0.6–2.5)</td>
<td>0.57</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.73 ± 0.08</td>
<td>1.68 ± 0.16</td>
<td>.292</td>
<td>0.05 (-0.05–0.16)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### 3.3.3 Hamstrings architectural comparisons:*

The muscle architecture measurements of the control limb (CL), uninjured limb (UL) and previously-injured limb (IL) of participants in the previously-injured group are shown in Table 3.5; with comparisons shown in Figure 3.9. A close to large effect size was observed for differences in pennation angle and fascicle length between limb groups. Pennation angle was larger (+1.54°, $d = 0.71$) and fascicle length was shorter (-0.58 cm, $d = 0.67$) in the IL when compared to CL.

Similarly, the IL was found to be more pennate (+1.06°, $d = 0.65$) and had shorter fascicles (-0.4 cm, $d = 0.65$) when compared to the UL. The CL was also found to have longer fascicles in the ST (+1.03 cm) compared to the IL with a large effect size ($d = 1.65$).
Table 3.5. Muscle architecture comparisons between control limb (CL), uninjured limb (UL) and previously-injured limb (IL).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=10)</th>
<th>Previously-injured group (n=5)</th>
<th>CL versus IL</th>
<th>UL versus IL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean of both limbs (CL)</td>
<td>Uninjured limb (UL)</td>
<td>Previously-injured limb (IL)</td>
<td>Mean difference (95% CI)</td>
</tr>
<tr>
<td><strong>BF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT [cm]</td>
<td>2.27 ± 0.28</td>
<td>2.33 ± 0.11</td>
<td>2.26 ± 0.13</td>
<td>0.01 (-0.28–0.30)</td>
</tr>
<tr>
<td>PA [°]</td>
<td>16.6 ± 2.3</td>
<td>17.1 ± 0.9</td>
<td>18.2 ± 2.2</td>
<td>-1.54 (-4.25–1.18)</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>8.82 ±1.08</td>
<td>8.66 ±0.71</td>
<td>8.24 ± 0.58</td>
<td>0.58 (-0.55–1.71)</td>
</tr>
<tr>
<td><strong>ST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT [cm]</td>
<td>2.26 ± 0.27</td>
<td>2.26 ± 0.32</td>
<td>2.21 ± 0.37</td>
<td>0.05 (-0.30–0.41)</td>
</tr>
<tr>
<td>PA [°]</td>
<td>14.2 ± 2.6</td>
<td>14.4 ± 1.9</td>
<td>13.7 ± 3.0</td>
<td>0.48 (-2.75–3.71)</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>10.19 ± 0.54</td>
<td>9.08 ± 0.63</td>
<td>9.16 ± 0.70</td>
<td>1.03 (0.32–1.73)</td>
</tr>
</tbody>
</table>

3.3.4 Hamstrings visco-elastic property comparisons: The muscle visco-elastic property comparisons between limb groups (CL, UL and IL) are shown in Table 3.6. The BF was found to be stiffer in the IL (+9.2 Nm⁻¹, d = 1.28) compared to the UL. Oscillation frequency measured on the BF lower in the IL when compared to the CL (-1.0 Hz, d = 0.88) and UL (-0.7 Hz, d = 0.99). This measure was also smaller on the ST of the IL when compared to the UL (-0.5 Hz, d = 0.82).

Table 3.6. Visco-elastic property comparisons between control limb (CL), uninjured limb (UL) and previously-injured limb (IL).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=10)</th>
<th>Previously-injured group (n=5)</th>
<th>CL versus IL</th>
<th>UL versus IL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean of both limbs (CL)</td>
<td>Uninjured limb (UL)</td>
<td>Previously-injured limb (IL)</td>
<td>Mean difference (95% CI)</td>
</tr>
<tr>
<td><strong>BF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>259.7 ± 43.8</td>
<td>257.3 ± 3.7</td>
<td>266.5 ± 9.5</td>
<td>-6.9 (-50.4–36.7)</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.4 ± 1.4</td>
<td>18.1 ± 0.6</td>
<td>17.4 ± 0.8</td>
<td>1.0 (-0.5–2.4)</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.89 ± 0.21</td>
<td>1.81 ± 0.03</td>
<td>1.83 ± 0.08</td>
<td>-1.55 (-0.37–0.06)</td>
</tr>
<tr>
<td><strong>ST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness [Nm⁻¹]</td>
<td>234.3 ± 15.5</td>
<td>244.0 ± 6.0</td>
<td>245.9 ± 7.1</td>
<td>-11.6 (-27.6–4.4)</td>
</tr>
<tr>
<td>Oscillation freq [Hz]</td>
<td>18.2 ± 1.1</td>
<td>18.5 ± 0.5</td>
<td>18.0 ± 0.7</td>
<td>0.2 (-1.0–1.4)</td>
</tr>
<tr>
<td>Decrement</td>
<td>1.71 ± 0.12</td>
<td>1.84 ± 0.06</td>
<td>1.79 ± 0.03</td>
<td>-0.09 (-0.21–0.04)</td>
</tr>
</tbody>
</table>
Figure 3.9. Muscle architecture properties of the control limb (CL), uninjured limb (UL) and injured limb (IL).
3.3.5 Strength measures. Figure 3.10 shows the isometric knee flexion strength measured on both limbs of the control group across six different knee-joint angles. There was no significant difference between peak torque (PT) measured across all six knee-joint angles for both limbs. Therefore, a mean measurement of strength was calculated (similar to architectural and visco-elastic property measurements) for both limbs in the control group to obtain a control limb (CL) strength measurement during all isometric and isovelocity knee flexion strength testing.

Isometric knee flexion strength measured across six different knee angle positions for the CL, UL and IL are shown in Figure 3.11. Strength measurements of four previously-injured participants (compared to five for muscle architecture and visco-elastic measurements) were used for comparison because one participant was substantially (38–49%) weaker on strength measures. Informal post-test interaction suggested that the participant felt unfamiliar with the dynamometry tasks despite having undergone a prior familiarisation session; and there was a fear of maximal exertion due to his previous injury. Therefore, the author feels that the participant’s measurements should not be considered in the analysis of tasks requiring voluntary effort in order to maintain the external validity of findings. PT was found to be lower in the IL at the more extended positions with medium to large effect size (135°: -6.9%, $d = 0.69$; 155°: -9.6%, $d = 0.85$; 135°: -9.5%, $d = 0.71$).
Figure 3.10. Isometric knee flexor strength for both limbs in control group.

Figure 3.11. Isometric knee flexor strength for control limb (CL), uninjured limb (UL) and injured limb (IL).

Isolevelocity knee flexion strength values measured at 60°/s and 240°/s are shown in Table 3.7. Eccentric peak torque (EccPT) at 60°/s was lower (-9.1%, $d = 1.34$) in the IL compared to the UL. This difference in EccPT occurred when the knee was in a more flexed position with the knee angle of eccentric peak torque occurrence (EccPT Angle) being lower (-
7.0°, $d = 0.99$) in the IL compared to the UL. Strength measures were similar between groups at the faster (240°/s) testing velocity.

### Table 3.7. Mean differences in isovelocity knee flexion strength measures between CL, UL and IL.

<table>
<thead>
<tr>
<th></th>
<th>Control (n=10)</th>
<th>Previously-injured group (n=4)</th>
<th>CL versus IL</th>
<th>UL versus IL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean of both limbs (CL)</td>
<td>Uninjured limb (UL)</td>
<td>Previously-injured limb (IL)</td>
<td>Mean difference (95% CI)</td>
</tr>
<tr>
<td>EccPT [Nm]</td>
<td>218.2 ± 25.1</td>
<td>222.9 ± 12.5</td>
<td>204.3 ± 15.0</td>
<td>13.9 (-15.7–43.5)</td>
</tr>
<tr>
<td>EccPT_angle [°]</td>
<td>152.1 ± 18.2</td>
<td>157.2 ± 7.4</td>
<td>150.2 ± 6.8</td>
<td>1.9 (-18.9–22.7)</td>
</tr>
<tr>
<td>ConPT [Nm]</td>
<td>206.3 ± 22.8</td>
<td>203.9 ± 13.7</td>
<td>201.5 ± 12.0</td>
<td>4.8 (-21.8–31.4)</td>
</tr>
<tr>
<td>ConPT_angle [°]</td>
<td>136.3 ± 11.6</td>
<td>139.2 ± 9.9</td>
<td>142.9 ± 14.2</td>
<td>-6.3 (-9.6–22.2)</td>
</tr>
<tr>
<td>EccPT [Nm]</td>
<td>169.0 ± 19.3</td>
<td>166.2 ± 11.2</td>
<td>163.5 ± 10.3</td>
<td>5.5 (-17.0–28.0)</td>
</tr>
<tr>
<td>EccPT_angle [°]</td>
<td>131.3 ± 17.3</td>
<td>128.3 ± 12.4</td>
<td>133.1 ± 9.7</td>
<td>-1.8 (-18.5–22.1)</td>
</tr>
<tr>
<td>ConPT [Nm]</td>
<td>110.2 ± 20.1</td>
<td>108.3 ± 14.8</td>
<td>112.6 ± 13.0</td>
<td>-2.4 (-21.5–26.4)</td>
</tr>
<tr>
<td>ConPT_angle [°]</td>
<td>134.5 ± 17.7</td>
<td>141.5 ± 18.3</td>
<td>139.2 ± 11.3</td>
<td>-4.7 (-16.4–25.8)</td>
</tr>
</tbody>
</table>

EccPT–eccentric peak torque; EccPT_angle–angle of eccentric peak torque occurrence; ConPT–concentric peak torque; ConPT_angle–angle of concentric peak torque occurrence

#### 3.3.6 Muscle activation across muscle length during isometric strength test.

The EMG RMS amplitude of limb groups across the six different knee angles during isometric knee flexion testing are shown in Figure 3.12. For all limb groups, BF muscle activation was highest at a knee angle of 150°; both BF and ST activation were lowest at the most flexed position (knee angle, 90°). BF activation in the IL was also found to be lower (5.3–12.1%) across all knee angle positions than the UL.
3.3.7 Running kinematics and muscle activation. Average sprint performance
across the measurement distance (7m) was similar between both groups (previously-injured,
0.135 m/s; previously-uninjured, 0.138 m/s). Figure 3.13 shows the knee and hip flexion
angles across the gait cycle of sprinting for both the control and previously-injured group.
There was little observable difference in mean peak hip and knee flexion angles across the
gait cycle between limbs in the control group. A mean value of joint angles (knee and hip)
across the gait cycle was calculated for both limbs in the control group (CL) and compared to
similar kinematic variables for the UL and IL (Table 3.8). There was little difference between
joint angles across the gait cycle between groups. However, when joint angles of individual participant's IL over the gait cycle were plotted against CL (Figure 3.14), three out of four previously-injured participants exhibited lower peak knee flexion angle during the mid-late swing phase.

![Figure 3.13. Joint angles over gait cycle (toeoff to toeoff) for both control and previously-injured groups.](image-url)
### Table 3.8. Peak knee and hip flexion angle between limbs during stance and from mid to late swing phase.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Control (n=10)</th>
<th>Previously-injured group (n=4)</th>
<th>CL versus IL</th>
<th>UL versus IL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean of both limbs (CL)</td>
<td>Uninjured limb (UL)</td>
<td>Previously-injured limb (IL)</td>
<td>Mean difference (95% CI)</td>
</tr>
<tr>
<td><strong>Peak knee flexion angle [°]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stance</td>
<td>24.2 ± 12.3</td>
<td>23.4 ± 8.5</td>
<td>23.0 ± 7.5</td>
<td>1.2 (-13.4–15.8)</td>
</tr>
<tr>
<td>Mid-late</td>
<td>119.1 ± 13.5</td>
<td>118.4 ± 10.3</td>
<td>117.9 ± 11.2</td>
<td>1.2 (-15.5–17.9)</td>
</tr>
<tr>
<td><strong>Peak hip flexion angle [°]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stance</td>
<td>26.7 ± 10.4</td>
<td>26.4 ± 7.9</td>
<td>26.9 ± 8.8</td>
<td>-0.2 (-12.7–13.1)</td>
</tr>
<tr>
<td>Mid-late</td>
<td>86.8 ± 8.3</td>
<td>87.2 ± 8.1</td>
<td>88.2 ± 5.2</td>
<td>-1.4 (-10.6–13.4)</td>
</tr>
</tbody>
</table>

#### Figure 3.14. Joint angles over gait cycle (toeoff to toeoff) of individual previously-injured participants’ IL compared against CL.
Muscle activation characteristics of the BF and ST over the gait cycle are shown in Figure 3.15. BF activation during the middle swing phase was lower in the IL when compared to the CL (-0.05, $d = 0.75$) and UL (-0.11, $d = 0.82$). BF and ST activation were generally low (BF: 0.09–0.10; ST: 0.05–0.06) during the early swing phase across all limb groups.
3.4 Discussion

The purpose of the first part of this study was to determine the inter-session reliability of muscle architecture and visco-elastic property measurements using 2-D ultrasonography and myotonometry respectively. The main findings were that muscle architecture such as muscle thickness, pennation angle and fascicle length could be reliably determined between sessions by the same operator with high ICCs reported. This further substantiates the reliability of ultrasound measures found in previous studies (Lima, Carneiro, Alves, Peixinho & Oliveira, 2015; Timmins et al., 2014). On the other hand, visco-elastic property assessment utilising a handheld myotonometer showed weaker inter-session reliability for most variables. However, inter-session reliability was still good with stiffness measures of the biceps femoris exhibiting similar ICCs as architectural variables measured through. This suggests that the measurement methods of hamstrings architecture and visco-elastic properties utilised can be reliably interpreted in this study and future investigations.

3.4.1 Muscle architecture. When comparing muscle architecture characteristics between athletes with and without a prior unilateral HSI, it was found that the IL exhibited larger pennation angles and shorter fascicles on the BF. Although all prior hamstring injuries were self-reported, participants reported the injury to be on the lateral side of the posterior thigh, corresponding to the site of the BF. This suggests that a previous injury to the BF is associated with more pennate and shorter muscle fascicles. This finding mirrors that of a previous retrospective study looking at changes to architecture of the biceps femoris after a hamstring injury (Timmins et al., 2014). The main implication of this finding is that the maladaptation of the BF, particularly the presence of shorter fascicles which results in fewer in-series sarcomeres may be more likely to be damaged during powerful eccentric contractions characteristic of movements such as high-speed running (Brockett, Morgan & Proske, 2004).
Although the hamstring comprises an equally voluminous ST, little information is known about its role in the onset of HSIs. In this study, it was found that there is little difference in ST architecture between contralateral limbs in a previously-injured athlete. This suggests that either ST architecture has little effect on the onset of HSIs in the BF; or injuries to the BF have no consequential effect on ST architecture. Further studies utilising the recruitment of participants with a prior semitendinosus strain injury would prove useful in investigating the association between pennation angle and fascicle length with injury across the different knee flexors. To date, evidence from this study and prior studies (Timmins et al., 2015) can only suggest an association between BF architecture and injury, which may be either retrospective or prospective in nature.

3.4.2. Visco-elastic property. Previous assessments of hamstring flexibility have involved a variety of passive (Arnason, Tenga, Engebretsen & Bahr, 2004; Rolls & George, 2004) and active (Gabbe et al., 2005; Malliaropoulos, Isinkaye, Tsitas & Maffulli, 2011) methods. However, these assessment methods introduce several confounding variables associated with hamstring flexibility such as lumbar spine flexibility and neural extensibility. Therefore, contradicting effects of flexibility on hamstring injury risk have been reported (Gabbe et al., 2006; Watsford et al., 2010). In this study, stiffness measures of the BF were found to be higher on the IL compared to the UL. With the relatively passive nature of assessment utilising a hand-held myotonometer, which eliminated the influence of several confounding factors, coupled with the good inter-session reliability of stiffness measures, it is possible that poor hamstring flexibility due to BF stiffness could be associated with HSIs. Similarly, future work could consider using a prospective study design investigating the role of both hamstring muscle architecture and visco-elastic property in the onset of HSIs.

3.4.3. Knee flexor strength. When comparing the knee flexor isometric torque across knee angles, the IL was found to exhibit a strength deficit when compared to CL and UL at
more extended positions. This suggests that at longer muscle lengths, weak hamstring strength is associated with a prior HSI. It was also observed that the length-tension relationship curve of the IL plateaued more over the extended positions; and optimum length was shorter as compared to the CL and UL. This could be partially explained by the comparatively lower muscle activation found in the IL at these positions when compared to the other limb groups. This could also be attributed to the reduced interaction of cross-bridges as a consequence of the maladaptation in muscle architecture (i.e. shorter fascicles). In addressing the issue of reducing hamstring injury risk, it seems intuitive that a rightward shift in optimum length towards relationships exhibited in the UL would be effective. Therefore, the findings of this study support clinical recommendations that strengthening and rehabilitative exercises for individuals with a prior HSI should include strengthening performed towards the end-range of motion (at longer muscle lengths) (Sterling, Juli & Wright, 2001).

Isovelocity strength testing was conducted at two testing velocities in this study (60°/s and 240°/s). At both testing velocities, there was no substantial difference in ConPT produced by the hamstrings between limb groups. The similar ConPT values between limb groups mirrors the lack of bilateral differences found in previous studies (Bennell et al., 1998; Lee et al., 2009), suggesting that rehabilitation restores ConPT strength effectively after injury. At the slower testing velocity (60°/s), EccPT was observed to be lower in the IL compared to both CL and UL. In the comparison of EccPT_Angle, PT was observed to occur at a more flexed position in the IL compared to the UL. The combination of these observations highlights the relative weak eccentric strength of the IL at longer muscle lengths compared to the CL and UL. Therefore, in addition to recommendations to strengthen hamstring strength at longer muscle lengths, this strengthening should focus on eccentric modes of contraction. However, it is important to consider that the faster testing velocity (240°/s) would have provided greater
external validity due to the closeness to actual conditions of high-speed running. In this instance, there was no observable difference in EccPT and EccPTAngle between limb groups.

3.4.4. Sprinting kinematics. Besides looking at differences between strength measures, another purpose of this study was to determine the differences in sprinting kinematics and muscle activation between previously-injured and uninjured athletes. It has been postulated that the onset of HSIs occur during the late swing phase (Heiderscheit et al., 2005; Schache et al., 2009) and the findings of this study seem to provide evidence for this with peak hip flexion angle observed to be higher in this phase in the IL compared to CL for three out of four athletes. Although the difference was smaller (1.0°) than previously reported (1.9°) by Lee and colleagues (2009) in a study looking at kinematics during sub-maximal running, a prospective study showed that every degree of hip flexor flexibility increased the risk of sustaining a hamstring injury by 15% (Gabbe, Bennell & Finch, 2006). Therefore, this observed increase in hip flexor stiffness during sprinting could be a kinematic feature of athletes prone to HSIs while sprinting.

3.4.5. Limitations. There were several limitations in the current study. Firstly, due to the difficulty in recruiting athletes who had previously suffered a HSI, comparisons between groups could have limited external validity. However, interpretation of results was based mostly on mean differences, 95% CI and effect size (Cohen’s d) in order to provide a better understanding of any observed differences. Future work should consider systematic collaboration with physicians and clinical institutions to improve the success rate of recruiting participants with clinically diagnosed injuries. Besides providing a more controlled comparison, it will improve upon the validity of results reported in this study. Additionally, although the reliability of muscle architecture and visco-elastic properties was established in this study, the validity of measurements was not undertaken. However, previous literature has shown the strong validity of 2D-ultrasound data with cadaveric measurements (Blackburn,
Bell, Norcross, Hudson & Kimsey, 2009; Chleboun, France, Crill, Braddock & Howell, 2001; and myotonometry readings with various other visco-elastic measurement methods (Chuang, Wu & Lin, 2012; Gubler-Hanna, Laskin, Marx & Leonard, 2007). The retrospective design of this study is only able to highlight the associations between a previously-injured hamstring muscle and various structural and functional variables measured in this study. In order to determine the role these variables play in the onset of HSIs, a large-scale prospective study is warranted.

3.4.6. Conclusion. In summary, the results of this study suggest that the use of 2-D ultrasonography is reliable for measuring muscle architecture properties of the BF and ST. The use of a hand-held myotonometer in this study showed to be more reliable in measuring stiffness compared to other visco-elastic properties; however, the relatively high MDC compared to the measurement values suggests that further evidence of its reliability has to be shown before it can be established as a reliable measure of these measures. In the previously-injured hamstring, differences in various structural variables such as fascicle length, pennation angle and stiffness; and differences in strength, sprinting kinematics and muscle activation could be observed. The abundance of differences in both structural and functional measures in a previously-injured hamstring suggest that these may be factors underlying the mechanisms of HSIs, as well as the efficacy of intervention strategies. The further understanding of these factors drives the research questions of the subsequent studies in this PhD project.
Chapter 4: Muscle Activation Characteristics Across Different Hamstring Strengthening Exercises

4.1 Introduction

Due to the substantial time and financial cost of HSIs (Opar, Williams & Shield, 2012; Raysmith & Drew, 2016), a large body of research has been directed towards investigating the efficacy of various interventive strategies. These include both rehabilitative and strengthening exercises. Common interventions such as stretching (Heiderscheit, Sherry, Silder, Chumanov & Thelenm, 2010), massage therapy (Goldman & Jones, 2010) and sports specific drills (Veral, Slavotinek & Barnes, 2005) have reported mixed findings. Stronger evidence exists for advocating the use of targeted hamstring strengthening exercises through resistance training. Recent progression towards a more injury mechanism-specific perspective on exercise prescription, which is based on the notion that since HSIs typically occur during eccentric contractions, an improvement in eccentric strength should reduce injury risk. This has led to the popularity of eccentric strengthening exercises, of which, the Nordic hamstring lowers (NHL) exercise has become a fixture in most conditioning programmes (e.g. FIFA 11+). The efficacy of eccentric training is premised on the idea that HSIs occur during the late swing phase of high-speed running when the hamstrings, the biceps femoris long head (BFlh) muscle in particular, is undergoing a forceful eccentric contraction to decelerate the shank (Chumanov, Heiderscheit & Thelen, 2011). Therefore, by eccentrically strengthening the hamstrings, the risk of injury may be reduced as the muscle can withstand more forces during this phase. The reduced risk of re-injury (Croisier et al., 2012) and increase in strength measures (Guex, Lugrin, Borloz & Millet, 2016) associated with eccentric training have contributed to its increasing adoption as a feature of hamstring strengthening programmes.
Although the advocation of eccentric training based on the mechanism of an HSI is logical, it may be an incomplete approach without considering the length of the muscle during the onset of injury. In a study comparing the hamstring muscle length-tension relationship between the previously injured and un-injured limbs of participants, it was found that peak hamstring torque occurred at significantly shorter muscle lengths in the previously injured limb (Brockett, Morgan & Proske, 2004). Although the study was retrospective in nature, it seems to suggest that weakness during the lengthened-state of the muscle is associated with HSI, whether as a risk factor or an outcome predisposing the individual to re-injury. Therefore, an effective training exercise should involve eccentric strengthening of the hamstrings at a lengthened-state. As a biarticular muscle, the combined action of hip flexion and knee extension during the late-swing phase of high-speed running results in a substantial elongation stress of the hamstrings (Schache et al., 2012). By utilising a rudimentary quantification of elongation stress (hip flexion angle minus knee flexion angle) proposed by Guex and Millet (2013), it can be found that common exercises such as the seated leg-curl and NFLH are not performed under muscle length conditions representative of the mechanism of injury. In the case of the popularly prescribed NFLH, there is minimal elongation stress during the full range of motion (ROM) of the exercise. In the candidate’s view, a simple adjustment to exercise position of many common exercises by increasing the amount of hip flexion to induce a lengthened-state of the hamstrings while performing the exercise may largely improve its efficacy.

In addition to having a sound guiding principle towards evaluating the design and efficacy of hamstring exercises, it is also important to rely on empirical evidence. Surface electromyography (sEMG) has been widely used to characterise the muscle activation pattern of various hamstring exercises (Bourne et al., 2016; Ditroilo, De Vito & Delahunt, 2013; Zebis et al., 2013). Although these studies provide useful information such as the selective...
nature of muscle activation during exercises performed either about the knee (medial hamstrings) or hip (biceps femoris) (Bourne et al., 2016), they do not adequately characterise exercises over the full ROM at which they are performed. Given the body of literature (Guex, Degache, Morisod, Sailly & Millet, 2016; Orishimo & McHugh, 2015) investigating the muscle length-tension relationship and how its shift (peak torque generation at longer muscle lengths) is associated with reduced injury risk, it might be useful to characterise muscle activity across different phases of the exercise’s ROM corresponding to different muscle lengths. This characterisation will better the understanding of neuromuscular mechanisms underpinning the efficacy of different exercises. A more detailed profiling of the muscle activation during different strengthening exercises will also the prescription of exercises consistent with the aetiology of injury, as evidenced by research.

Therefore, the purpose of this study was to characterise different common and lengthened-state variants of hamstrings resistance training exercises by understanding the (i) muscle activation pattern across phases of exercise ROM and (ii) muscle elongation at end ROM. The author hypothesises that hamstring muscle activation pattern would differ between exercises and phases of ROM during each exercise; and lengthened-state variants will exhibit higher muscle elongation stress during end ROM.

4.2 Methods

4.2.1 Participants. Eleven resistance-trained males (age, 22.1 ± 4.3 years; height, 1.77 ± 0.05 m; body mass 78.8 ± 8.0 kg) with an average hamstring training frequency of 7.8 ± 3.7 sessions/month participated in this cross-sectional study. Participants had no history of HSIIs in the previous 18 months and have had no surgeries to the back and lower limbs. All participants provided written informed consent prior to the start of the study which received
approval from the Loughborough University Ethics Committee (Human Participants) (Appendix 2) and the Nanyang Technological University Institutional Review Board (Appendix 3).

4.2.2 Exercise protocol. The six exercises (Figure 4.1) were chosen based on a combination of a review of scientific literature and careful consideration of how specific exercises can be modified to produce lengthened-state variants. They were grouped as exercises performed about either the knee (three) or hip (three) joints. The three knee-based exercises were the conventional Nordic hamstring lowers (CN), assisted NHL with hip flexion (AN) and seated leg-curl with hip flexion (SLC); and the three hip-based exercises were the inclined hip-extension (IHE), “good morning” (GM) and straight-leg hip-extension (SHE). All exercises were performed with load except for the CN which is a maximal effort calisthenic exercise. Exercises were performed with a 2-3s consistent pace during eccentric phases. Due to safety concerns, assistance was provided during the concentric phase of some exercises (SLC and SHE) while for the GM and IHE, it was performed with an accelerated concentric phase. A custom brace was fabricated and used during the CN and AN task to maintain a hip joint angle of 180° and 60° respectively. A pulley system utilising a harness and weights was used during the AN to provide assistance when necessary. This assistance was occasionally utilised as some participants would find it more difficult to reach the termination point of the exercise. A commercial knee brace was used to maintain a knee angle of 180° for the GM and SHE tasks. This brace was secured on the left limb.
4.2.3 Test procedure. On a separate day before the actual test sessions, participants were familiarised with the exercises used in the study. The familiarisation procedure involved a demonstration and practice efforts guided by verbal feedback from the investigators. Once it had been determined that participants were technically competent, a progressive loading to
failure protocol was utilised to determine each participant’s three repetition-maximum (3RM) load (except for the conventional NHL). After adequate rest, participants were also familiarised with the knee flexion and hip extension tasks used to elicit maximal voluntary contraction (MVC) during isovelocity movements.

Participants reported for actual testing on two separate occasions. Participants performed three exercises on each occasion (i.e. all three knee-based or hip-based exercises, randomised between sessions). Each testing session began with participants performing isovelocity contractions for the hamstrings. After a period of rest (20 minutes), participants completed a single set of three repetitions of each of the (knee- or hip-based) exercises at the predetermined 3RM load in a randomised order. A five-minute rest period was taken between exercises. All data was sampled on the right leg which was the involved limb during unilateral exercises.

4.2.4 Maximal voluntary contraction. Participants performed knee and hip flexion/extension isovelocity contractions on a dynamometer (Con-Trex, CMV AG, Dübendorf, Switzerland). The MVCs were performed at three different knee-joint angle and hip-joint angle configurations (Figure 4.2). Prior to actual testing, participants performed a series of progressive warm-up efforts comprising isometric MVCs at a knee/hip angle of 135° (3 × 50%, 3 × 75% and 1 × 90%) (Lanza et al., 2017); and isovelocity (60°/s) contraction efforts at perceived 50% and 75% of maximum effort. Subsequently, participants performed two sets of two concentric/eccentric cycles at 60°/s. Knee or hip flexion/extension isovelocity MVC tasks performed were specific to the type of exercises (knee- or hip-based) being performed on the day (i.e. only the hip isovelocity task was performed on the day when three hip-based exercises were performed; and both knee isovelocity tasks were performed on the
day when knee-based exercises were performed). A testing velocity of $60^\circ$/s was utilised in order to match the velocity at which the exercises are typically performed.

4.2.5 Electromyography. Surface electromyographic (sEMG) signals were recorded from the superficial hamstrings (biceps femoris (BF) and semitendinosus (ST) using the Delsys Trigno System (Delsys, Boston, Massachusetts, USA). Skin preparation included shaving, light abrasion and cleaning with alcohol. Electrodes were positioned over the belly of each muscle, parallel to muscle fibre orientation. Placement sites were at the mid-point of thigh length (measured as the distance between the knee-joint space and greater trochanter) with reference from the crease of the popliteal fossa (Lanza, Balshaw & Folland, 2017).

<table>
<thead>
<tr>
<th>Movement</th>
<th>Knee-joint angle</th>
<th>Hip-joint angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion/extension</td>
<td>$135^\circ$</td>
<td>$120^\circ$</td>
</tr>
<tr>
<td>Knee flexion/extension</td>
<td>$135^\circ$</td>
<td>$60^\circ$</td>
</tr>
<tr>
<td>Hip extension/flexion</td>
<td>$180^\circ$</td>
<td>$135^\circ$</td>
</tr>
</tbody>
</table>

**Figure 4.2.** Knee-angle and hip-angle configuration positions of isovelocity tasks

4.2.6 Exercise range of motion. 2D sagittal plane video recordings were simultaneously taken during the performance of all exercises and MVC tasks. Markers placed on the lateral malleolus, lateral epicondyle of femur, greater trochanter and acromion were digitised offline using a 2-D motion analysis software (Kinovea 0.8.15, Kinovea) to obtain
measures of knee-joint and hip-joint angles. Elongation stress was measured by subtracting hip-joint angle from knee-joint angle (Guex & Millet, 2013).

4.2.7 Data analysis. sEMG signals were sampled at 2 kHz using a A/D converter (CED, Cambridge, UK that enabled synchronisation through Spike 2 software (CED) with force recordings during MVC tasks. sEMG signals were corrected for a 48 ms lag present in the Trigno EMG system and band-pass filtered (Butterworth, 4th order, zero-lag) between 6 and 500 Hz (Balshaw et al., 2017). Joint angle information from video data was used to differentiate the ROM (during the eccentric phase) preceding the termination of each exercise into three 15° sectors (Figure 4.3). The termination point of each exercise was determined based on a combination of the visual inspection of the video recording and sEMG levels. For each sector, the filtered sEMG signal (RMS Amplitude) during the eccentric phase of each exercise was normalised to values obtained during the isovelocity MVC tasks with knee- and hip-joint angle configurations specific to the exercise performed.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Sector</th>
<th>Range before termination of exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-15°</td>
<td>Preceding end ROM</td>
</tr>
<tr>
<td></td>
<td>15-30°</td>
<td>Preceding end ROM</td>
</tr>
<tr>
<td></td>
<td>30-45°</td>
<td>Preceding end ROM</td>
</tr>
</tbody>
</table>

Figure 4.3. Sample illustration of sector definitions (CN exercise shown)
4.2.8 Statistical analysis. All statistical analyses were performed using SPSS 24.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics (mean and standard deviation) of muscle activation variables were computed across exercise, muscle and sectors. A $2 \times 3$ two-way (Muscle $\times$ Sector) repeated measures analysis of variance (ANOVA) was performed on muscle activation variables for each of the six exercises. One-way ANOVA was performed on calculated BF/ST nEMG ratios between exercises. The level of significance was set at $P < .05$ for all analyses. Bonferroni-corrected post hoc tests were performed accordingly. Greenhouse–Geisser’s epsilon adjustment was used in all cases when Mauchley’s test indicated that the sphericity assumption had been violated.
4.3 RESULTS

Strength measures from the normalisation tasks are shown in Figure 4.4. Mean BF and ST normalised EMG (nEMG) activity across exercises and sectors are shown in Table 4.1 and Figure 4.5. BF activity was highest during the CN (start: 40.6%, middle: 58.2%; end: 75.2%) and lowest during the SHE (start: 25.5%, middle: 32.9%; end: 50.1.2%). ST activity was similarly highest during the CN (start: 45.2%, middle: 70.4%; end: 11.3%) but lowest during the IHE (start: 17.4%, middle: 39.0%; end: 52.7%). There were differences in BF and ST activation across the start (30-45°), middle (15-30°) and end (0-15°) sectors. Post hoc analyses revealed that hamstring muscle activity became progressively higher (end > middle, middle > start, end > start) across the exercise ROM for all exercises except the SHE (end > middle, end > start).

Figure 4.4. Eccentric peak torque across three normalisation tasks; HJA-hip-joint angle; KJA-knee-joint angle
Figure 4.5. Mean normalised (to isovelocity MVC at 60°/s) EMG activity of BF and ST during exercises across three 15° sectors preceding end ROM.
The eccentric BF/ST activation ratio during the final sector for the exercises can be found in Figure 4.6. A significant main effect was observed for exercise during this sector ($p = 0.024$; CN < IHE & SHE; SLC < IHE & SHE).

![Hamstrings activation during eccentric phase](image)

**Figure 4.6** Biceps femoris (BF) to semitendinosus (ST) activation ratio during final 15° sector of exercises.

The elongation stress on the hamstrings during the end ROM of each exercise can be found in Table 4.2. Muscle elongation (KJA-HJA) during end ROM was highest in the SLC (88.6°) and lowest during CN (-54.1°).
Table 4.1. Comparison of normalised EMG (nEMG) activity across exercise sectors for six different hamstring strengthening exercises.

<table>
<thead>
<tr>
<th>Exercise sectors</th>
<th>Interaction</th>
<th>ANOVA Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \eta^2_p )</td>
</tr>
<tr>
<td></td>
<td>Start</td>
<td>Middle</td>
</tr>
<tr>
<td>CN</td>
<td>0.074</td>
<td>0.149</td>
</tr>
<tr>
<td>AN</td>
<td>0.023</td>
<td>0.236</td>
</tr>
<tr>
<td>SLC</td>
<td>0.362</td>
<td>0.557</td>
</tr>
<tr>
<td>IHE</td>
<td>0.018</td>
<td>0.399</td>
</tr>
<tr>
<td>GM</td>
<td>0.038</td>
<td>0.218</td>
</tr>
<tr>
<td>SHE</td>
<td>0.038</td>
<td>0.102</td>
</tr>
</tbody>
</table>

Notes: CN = conventional nordic hamstring lowers; AN = assisted nordic hamstring lowers with hip flexion; SLC = seated leg-curl with hip flexion; IHE = inclined hip extension; GM = “good morning”; SHE = straight-leg hip extension; BF = biceps femoris; ST = semitendinosus. \( \eta^2_p \) = partial eta squared; \( \beta \) = observed power. Significant \( P \)-values (\( P < .05 \)) are shown in bold.

Exercises: GM = “good morning”; SHE = straight-leg hip extension; SLC = seated leg-curl with hip flexion; IHE = inclined hip extension; CN = conventional nordic hamstring lowers; AN = assisted nordic hamstring lowers with hip flexion. 

Values: \( P > .05 \) (not shown in bold).
4.4 Discussion

The purpose of this study was to characterise different common and lengthened-state variants of hamstrings resistance training exercises by examining muscle activation pattern across the range of exercise as well as the muscle elongation stress experienced while performing the exercise. The major finding of this study was that muscle activity during the eccentric phase of exercises examined differed across the ROM at which it was performed. This suggests that in previous studies comparing muscle activation across different exercises (Bourne et al., 2016; Zebis et al., 2013), a mean value of muscle activation across the full ROM may not provide adequate information to fully evaluate the efficacy of these exercises, especially at larger joint angles where muscle length is longer. With strong evidence (Brockett et al., 2004; Gao, Wineman & Waas, 2008) suggesting that weakness during the lengthened-state of the muscle is associated with HSI risk, understanding muscle activation characteristics at longer muscle lengths of various exercises may be more relevant in directing research focused on intervention strategies to reduce injury risk.

Similar to previous studies (Bourne et al., 2016; Tillaar, Solheim & Bencke, 2017), the CN was found to exhibit substantially higher levels of BF and ST activation (especially in the final sector preceding the termination of the exercise found in this study) compared to the other exercises. However, when this information is viewed in tandem with elongation stress measurements (CN being the lowest among all exercises), the effectiveness of the CN as a hamstring strengthening exercise at longer muscle lengths may be negated. Therefore, the

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Knee-joint angle at end ROM [˚]</th>
<th>Hip-joint angle at end ROM [˚]</th>
<th>Elongation stress [˚]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>121.7 (9.3)</td>
<td>175.8 (7.9)</td>
<td>-54.1</td>
</tr>
<tr>
<td>AN</td>
<td>138.8 (10.5)</td>
<td>110.3 (8.4)</td>
<td>28.5</td>
</tr>
<tr>
<td>SLC</td>
<td>160.1 (5.1)</td>
<td>71.5 (5.9)</td>
<td>88.6</td>
</tr>
<tr>
<td>IHE</td>
<td>177.3 (2.1)</td>
<td>101.4 (4.6)</td>
<td>75.9</td>
</tr>
<tr>
<td>GM</td>
<td>164.3 (5.8)</td>
<td>119.5 (6.1)</td>
<td>53.8</td>
</tr>
<tr>
<td>SHE</td>
<td>175.8 (2.4)</td>
<td>108.2 (6.2)</td>
<td>67.6</td>
</tr>
</tbody>
</table>
author suggests that a comprehensive evaluation of efficacy of exercises should consider both muscle activation and elongation stress during the instance of activation. In this study, the SLC was found to exhibit high BF (60.7 ± 7.4%) and ST (75.9 ± 13.4) activation levels with the largest elongation stress (+88.6°) during the end ROM of the exercise. Although elongation stress is best quantified in vivo, the quantification of elongation stress using measurements of hip and knee angle in this study provide a relative comparison of the stresses on the hamstrings across various exercises. It is evident that exercises which exhibit a consistently large knee angle and small angle at the instance of highest hamstring activation throughout the exercise ROM place a larger amount of stress on the hamstrings (Guex & Millet, 2013). This suggests that the SLC may be the most effective of all exercises examined as a prophylactic measure against HSIs. A further study is warranted to evaluate the efficacy of the SLC as a hamstring strengthening exercise to reduce the risk of HSI among individuals.

Contrary to a previous (Bourne et al., 2016) which found higher levels of BF activity during hip-based exercise, no preferential recruitment of muscle was observed across hip-based exercises. On the other hand, there was a pronounced selective recruitment of the ST found during the final sector of movement in knee-based activities. This may be explained by the larger sagittal plane moment arm at the knee of the ST compared to the BF (Thelen, Chumanov & Hoerth, 2005). To the author’s knowledge, this is the first study utilising a brace to fixate the hip angle during the performance of the CN and AN. This was done to minimise the changes in hip angle across the range of the exercise because most individuals tend to flex the hip as the task becomes progressively harder (by reducing the moment arm of the movement). Therefore, the use of a brace would ensure that the moment arm comprising the upper body about the knee-joint would remain constant throughout the full range of the exercise. Due to the more controlled nature of movement, the results of this study in relation
to muscle activity during these exercises could be interpreted with higher confidence than previous studies (Buhmann, Shield & Sims, 2017; Tillar et al., 2017) looking at Nordic hamstring lowers and similar variations. In these studies, although no information was available on the changes in hip flexion angle throughout the exercises, it would be expected that participants would have intuitively flexed the hip to minimise the intensity of the exercise (by reducing the moment arm of the movement) throughout the range of movement.

There were a few limitations to this study. Firstly, although the purpose of this study was to investigate muscle activation during the eccentric phase of movement, exercises apart from the CN and AN could not be performed without a concentric phase. Therefore, in order to reduce the effect of a prior concentric contraction on the subsequent eccentric contraction, participants were either assisted through the concentric phase whenever possible or instructed to perform the concentric phase as quickly as possible (when safe assistance was not possible). This may have had a negligible confounding effect on muscle activation values measured, the extent to which still warrants further investigation. Secondly, as the testing involved repeated bouts of eccentric contractions, participants recruited were strength trained at the hamstrings in order to ensure the testing could be carried out in a controlled and safe manner. This means that the findings presented may not be transferred directly to other athletes who do not have such as strong emphasis on hamstring strengthening during their regular training.

In summary, differences in muscle activity across the range of hamstring strengthening exercises examined in this study suggest that besides contraction type, joint angle also influences muscle activation during these exercises. The high BF activity and muscle elongation of the SLC during end-ROM suggest that it may be an effective hamstring strengthening exercise. The efficacy of such exercises targeted at strengthening the muscle at longer muscle lengths in reducing HSI risk should be further investigated.
Chapter 5: Architectural and Functional Adaptations of Hamstrings

Following a 12-week Lengthened-state Training Programme

5.1 Introduction

Although hamstring strain injuries (HSIs) have been shown to have high individual and group costs (Elliot et al., 2011; Woods et al., 2002), which necessitates the need for an effective intervention strategy to reduce the risk of HSIs, limited systematic information exists on the effectiveness of general intervention strategies. These strategies include exercises such as stretching, strengthening (concentric and eccentric), movement dysfunction correction, neuromuscular strategies and general intervention programmes such as warm-ups and aerobics (Goldman & Jones, 2010). The effectiveness of these interventions has been found to be mixed with some authors reporting stretching to be ineffective (Heiderscheit et al., 2010), while others recommended increasing active range of motion (ROM) through static stretching and strengthening programmes (Brooks, Fuller, Kemp & Reddin, 2006; Worrell & Perrin, 1992). Training targeting an improvement in balance was found to be ineffective while strengthening exercises reported conflicting results depending on the type of exercise performed (Goldman & Jones, 2010). Some authors recommended a combination of concentric and eccentric exercises (Askling, Karlsson & Thorstensson, 2008) while others deemed the use of eccentric strength training as sufficient (Engebretsen et al., 2010). From the results of various studies, it is evident that scientific opinion on the efficacy of common preventive exercises is contradicting.

The onset of HSIs commonly takes place while susceptible individuals are engaging in high-speed running (Brooks et al. 2006), specifically during the late swing phase when the hamstrings are subject to a high level of elongation stress. During this phase of running, the hamstrings must undergo eccentric contraction in order to decelerate the forward movement.
of the lower-limb (Higashihara et al. 2015; Schache et al. 2012). Therefore, the recent body of literature on the efficacy of hamstring strengthening exercises have skewed towards eccentric-focused training exercises.

A large number of studies have focused on the Nordic hamstring lowers (NHL) as a prophylactic exercise for HSIs. This is largely due to the combination of the eccentric nature of the exercise as well as the ease of carrying out the movements required. Various studies have evidenced that NHL training programme can successfully reduce the occurrence of HSIs in both professional and recreational athletes (Petersen et al. 2011; van der Horst et al. 2015). Based on previous published literature (Timmins et al. 2016) and the results from the preceding chapter of this thesis (Chapter 4), it has been postulated that athletes with shorter fascicles in the biceps femoris (BF) may be at higher risk of sustaining a HSI. Recent studies looking at changes to hamstrings architecture after a period of NHL training have found 20-24% increases in biceps femoris fascicle (Alonso-Fernandez et al. 2017; Bourne et al. 2017). This increase in fascicle length, likely a result of sarcomerogenesis, could be an underlying physiological adaptation responsible for the reduction in risk of injury after a period of NHL training. This is likely due to longer fascicles being less susceptible to overstretching and damage resulting from excessively forceful eccentric contractions (Brockett et al. 2004).

Previous studies have also found that NHL training is associated with increases eccentric peak produced by the knee flexors (Delahunt et al. 2016; Iga et al. 2012). Adaptations in the torque-angle relationship resulting from sustained NHL training have also been reported (Brockett et al. 2001).

Although NHL training has been established with positive results in reducing HSI risk, there are limitations to the exercise which may not constitute its relevance as an injury-mechanism specific intervention. One such limitation is the inability of the NHL to fully load the muscle through its range of motion because of the exponential loading until a
“breakpoint” (approximately 30-50°), leading to the premature cessation of exercise in most cases (Ditroilo et al. 2013; Alt et al. 2017). Furthermore, due to the nature of the NHL as a maximal eccentric exercise, the physiological demands on the muscle during its execution makes it difficult to prescribe in the early phases of rehabilitation processes (Tyler et al. 2015). Furthermore, the prescription of the NHL movement involves minimal hip flexion (Petersen et al. 2011). This suggests that the NHL does not strengthen the hamstrings at the hip flexed position achieved during the late swing phase (Chumanova et al. 2011), where most HSIs are thought to occur. There is also very minimal elongation stress on the muscle throughout the exercise which was determined in Chapter 3 of this thesis.

Based on the existing information on the efficacy of NHL training, the author suggests that an alternative exercise involving the gradual eccentric loading of the hamstring in a lengthened state may be more effective as a prophylactic exercise to reduce HSI risk. In only one previous study identified which investigated the efficacy of training the hamstring muscle in a lengthened-state, adherence to a dynamometry based lengthened-state training programme was shown to reduce the rates of reinjury, while also improving strength in the involved leg to pre-injury levels (Tyler et al. 2015). However, to the author’s knowledge, there have been no studies conducted which have sought to characterise the architectural and functional adaptations of the hamstring muscles following a period of lengthened-state training which would provide valuable information on the efficacy of an injury-mechanism specific intervention to HSIs.

Therefore, the purpose of this study was to compare the architectural and eccentric strength changes of the hamstrings following a 12-week eccentric training programme, consisting of either control, Nordic hamstring lowers or lengthened-state eccentric training conditions. It is hypothesised that eccentric training in a lengthened state will be more effective than performing NHLs in inducing changes relevant to reducing HSI risk.
5.2 Methods

5.2.1 Participants. 48 recreationally active male participants were initially recruited for this study. However, five participants dropped out of the study due to either failure to comply to the training programme or missed the measurement sessions. Therefore, 43 participants’ data was used in this study. Participants had no history of HSIs in the previous 18 months and have had no surgeries to the back and lower limbs. All participants provided written informed consent prior to the start of the study which received approval from the Loughborough University Ethics Committee (Human Participants) (Appendix 4) and the Nanyang Technological University Institutional Review Board (Appendix 5). All participants were matched for knee flexor strength and body mass before being randomly assigned into control (CON; \(n = 15\)), Nordic hamstring lowers (NHL, \(n = 14\)) and lengthened-state training (LST, \(n = 14\)) groups. Participants characteristics are described in Table 5.1. Physical activity levels (recreational) was assessed using the International Physical Activity Questionnaire (short format) (Craig et al. 2003) (Appendix 6).

<table>
<thead>
<tr>
<th>Group</th>
<th>(n)</th>
<th>Age [years]</th>
<th>Height [m]</th>
<th>Body mass [kg]</th>
<th>Physical activity [MET-min/week]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>15</td>
<td>24.3 ± 2.8</td>
<td>1.78 ± 6.5</td>
<td>74.5 ± 6.2</td>
<td>1410 ± 449</td>
</tr>
<tr>
<td>NHL</td>
<td>14</td>
<td>25.5 ± 3.6</td>
<td>1.77 ± 7.7</td>
<td>75.5 ± 14.2</td>
<td>1501 ± 430</td>
</tr>
<tr>
<td>LST</td>
<td>14</td>
<td>24.4 ± 3.7</td>
<td>1.77 ± 5.8</td>
<td>76.7 ± 11.2</td>
<td>1539 ± 478</td>
</tr>
</tbody>
</table>
5.2.2 **Study design.** Participants reported to the test location on five occasions for testing and completed 34 supervised training sessions. All participants underwent a familiarisation session which involved a run-through of all functional testing procedures. Subsequently, they reported to the laboratory for two pre-training strength measurement sessions (separated by at least five complete days or rest). Ultrasound measurements of muscle architecture were taken on the second of these measurement sessions. Participants then underwent 12 weeks of either no training (CON), Nordic hamstring lowers (NHL) or lengthened-state training (LST). After at least 48 hours of rest proceeding the end of the last training session, participants reported for two duplicate post-test strength measurement sessions (at least five days apart). Similarly, ultrasound measures were taken on the second of these sessions. All participants were instructed to continue their usual physical activity and diet habits throughout the duration of the study.

5.2.3 **Hamstrings architecture assessment.** During the measurement session, the participant was instructed to lay prone on a bed with his feet hanging off the edge. Ultrasound images were taken along the longitudinal axis of the muscle belly using a two-dimensional, B-mode ultrasound (5-10 MHz, scanning width 92 mm and depth 65 mm; EUP-L53L, Hitachi EUB-8500). The linear array ultrasound probe was placed on the skin (lubricated by a layer of gel) over the site to be scanned. Care was taken to align the probe longitudinally and perpendicular to the surface of the posterior thigh. Minimal pressure was used to stabilise the probe on the skin to reduce its possible influence on the accuracy of measurement results (Klimstra et al., 2007). At least two clear images were taken at each site for both legs.

All images were exported and analysed offline (Kinovea 0.8.15, Kinovea). Methods of measurement for muscle architecture properties were similar to those used in Chapter 3 (Figure 3.3). Muscle thickness (MT) was defined as the perpendicular distance from the
deeper aponeurosis to the superficial aponeurosis. A fascicle was marked out on the image and the pennation angle (PA) was defined as the average of angles formed between this fascicle with the superficial and deeper aponeuroses. Fascicle length (FL) was defined as the length of one complete fascicle. When the fascicle could not be fully seen, fascicle and aponeuroses lines were extrapolated to obtain a measurement. For both pennation angle and fascicle length, five fascicles were measured on the same image to obtain an average measurement.

5.2.4 Strength assessment. The participant was positioned on an isokinetic dynamometer (Con-Trex MJ, CMV AG, Duebendorf, Switzerland) with hip flexion angle on the machine set to 70° (Figure 5.1). The femoral lateral epicondyle was aligned to the dynamometer crank’s center of rotation during an isometric contraction (knee joint angle approximately at 135°). Two three-point belts were fastened across the torso and additional straps were used to secure the distal part of the thigh and hips to the seat of the machine. The crank arm was securely fastened to the back of the shank over the gastrocnemius muscles. A shin guard lined with a thin layer of high-density foam was placed two centimeters above the medial malleolus to serve as padding. The uninvolved leg was rested on an elevated frame. The positioning parameters of participants on the dynamometer (e.g. seat height, crank eight etc.) was determined during the familiarisation session and utilised throughout all measurement sessions.

All measurements were taken on the right leg of participants. After a series of progressive warm-up efforts comprising isometric voluntary contractions at a knee angle of 135° (3 × 50%, 3 × 75% and 1 × 90% of perceived maximum effort) (Lanza et al., 2017); and isovelocity (50°/s) contraction efforts at perceived 50% and 75% of maximum effort, followed by two sets of two concentric/eccentric cycles at 50°/s at maximal effort.
Participants were instructed to “pull” as hard as possible during the whole duration of each effort (separated by 1 minute of rest between sets).

Torque signals were sampled at 2KHz and fed into a desktop computer running Spike 2 software (CED, Cambridge, UK) and smoothed at 15 Hz before further analysis (Balshaw et al., 2017). Torque values were corrected for passive torque measured at the start of testing. The highest torque value attained by each participant across all efforts during the eccentric phase during duplicate pre- and post-training measurements was selected for analysis.

![Participant position on dynamometer during strength assessment.](image)

**Figure 5.1.** Participant position on dynamometer during strength assessment.

5.2.5 Training programme. Participants in the training intervention groups completed a training programme comprising 34 supervised sessions over a continuous period of 12 weeks (Table 5.2). The training programme was designed to gradually increase training
volume in the beginning before maintaining a uniform training load for the second-half of the programme. Each session was separated by at least 36 hours of recovery and participants were instructed to avoid lower-body strength training outside the training programme prescribed in this study. All participants successfully completed the set number (34) of training sessions. At the start of each training session, participants performed a standardised warm-up which included a 5-min stationary cycling effort (70 rpm, 150W) followed by performing set static hamstring stretches. Sets of exercises during the training programme were separated by two minutes of rest. Constant and consistent verbal feedback was provided to all participants during all training sessions.

Table 5.2. Resistance training programme detailing volume of exercise over 12 weeks.

<table>
<thead>
<tr>
<th>Week</th>
<th>Session 1 (sets × repetitions)</th>
<th>Session 2 (sets × repetitions)</th>
<th>Session 3 (sets × repetitions)</th>
<th>Total number of repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 × 6</td>
<td>2 × 6</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>2 × 6</td>
<td>2 × 6</td>
<td>2 × 6</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>2 × 9</td>
<td>3 × 7</td>
<td>3 × 7</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>3 × 8</td>
<td>3 × 9</td>
<td>3 × 10</td>
<td>81</td>
</tr>
<tr>
<td>5</td>
<td>4 × 8</td>
<td>4 × 8</td>
<td>4 × 9</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>4 × 9</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>116</td>
</tr>
<tr>
<td>7</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>120</td>
</tr>
<tr>
<td>8</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>120</td>
</tr>
<tr>
<td>11</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>120</td>
</tr>
<tr>
<td>12</td>
<td>4 × 10</td>
<td>4 × 10</td>
<td>-</td>
<td>80</td>
</tr>
</tbody>
</table>

**Total:** 1097
5.2.5.1 Nordic hamstring lowers (NHL). NHL were completed in a custom-built Nordic rig (Figure 5.2). Participants kneeled on a padded board and were secured to the rig with ankle straps placed approximately 4 centimeters above the medial malleolus. The ankle straps were connected to strain gauges which sampled force signals at 2 KHz. This signal was fed into an A/D converter and recorded in the Spike 2 software (CED, Cambridge, UK). This force value was presented on a screen positioned in front of the participant (within the line of vision); with the participant’s highest torque measured across all previous training sessions indicated on screen to provide visual feedback. Participants began the exercise in a 90° knee flexed position with minimal hip flexion. They were instructed to keep their elbows flexed with shoulders adducted and externally rotated while lowering themselves forward. Participants were supervised to ensure the hip did not flex excessively during the movement. At the point when participants reached the “break” point in the exercise, they cushioned their fall with the use of their upper limbs onto a mat. Subsequently, participants were told to return to the starting position of the movement as soon as possible using their arms for support. When participants became strong enough to perform the task comfortably (“break” point of less than 30° above the horizontal), they performed the task with a weighted vest (with training load increments of 1 kg).
5.2.5.2 Lengthened-state training (LST). Participants were positioned in a modified leg curl machine (LifeFitness, Chicago, USA), with a starting position hip angle of 60° (Figure 5.3). The knee joint center was aligned with the machine arm’s center of rotation. The seat position and lever arm length adjustments unique to each participant were noted and used throughout all training sessions. Tightening straps were used to secure the chest and hip in order to stabilise the body during the exercise. Participants placed their shank on the support arm of the machine (Figure 5.3C) and completed unilateral efforts, alternating between legs, with two-minutes rest between sets. During the first training session, each participant’s six repetition-maximum (6RM) load was determined through progressive loading and verbal feedback.

A single set of exercise comprised of both eccentric and concentric efforts. The exercise began with the concentric phase by using both legs (knee flexion) with assistance from an investigator in order to minimise the intensity concentric efforts. Participants were also instructed to perform the concentric phase as swiftly as possible. When both knees were fully flexed (Figure 5.3A), the participant was instructed to either straighten or slide out the leg laterally away from the shank support (depending on the side of the involved leg). They were then instructed to
unilaterally perform the eccentric phase of the exercise which involved a controlled knee extension movement back to the starting position of the exercise (Figure 5.3B). They were told to maintain this eccentric phase of movement across a duration of approximately two to three seconds. The progression of the training was accomplished in 2 kg load increments and by increasing ROM (i.e. beginning and ending the exercise in a more extended position (Figure 5.3C)).

![Figure 5.3](image)

**Figure 5.3.** (A) Concentric phase using both limbs ending in a knee-flexed position; (B) Eccentric phase in a controlled manner (over 2-3s) using one limb; (C) Hip angle position (60°) during exercise and progression of knee ROM across training sessions (from 143° to 166°).

### 5.2.6 Training progression

The determination of progression was based on subjective ease of task completion assessed by both participant and investigator. This was to ensure that each set of exercise was of maximal intensity for the session. Upon completion of each set of exercise, subjective rating of effort was assessed (Appendixes 8 and 9) to
determine if loading is be conducted for the subsequent set. This was done to control training intensity and ensure the progressive nature of the exercise programme.

### 5.2.7 Statistical analysis

All statistical analyses were performed using SPSS 24.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics (mean and standard deviation) of muscle architecture variables and eccentric strength measures were computed across training groups and during pre- and post-training measurement sessions. In order to compare between-group responses to the training interventions, a two-way mixed-measures analysis of covariance (ANCOVA) [group (CON vs. NHL vs. LST) \(\times\) time (pre vs. post)] was conducted, pre-intervention values used as covariates. Bonferroni-corrected post hoc tests were performed accordingly when group \(\times\) time interaction effects were significant in order to determine pairwise pre-training adjusted differences between groups. The level of significance was set at \(P < .05\) for all analyses.

### 5.3 Results

The muscle architecture of the biceps femoris variables measured through ultrasonography during pre- and post-training measurement sessions are presented in Table 5.3 and Figure 5.4.

Changes to biceps femoris pennation angle and fascicle length were similar before and after the 12-week training period. However, a group effect (\(p = < 0.001\)) for muscle thickness was observed after adjustment for pre-training measures. Post-hoc pairwise comparisons showed that the change in muscle thickness was larger than that of the CON group in the NHL (\(+6.4\%\)) and LST (8.9%). The change in pre-training adjusted muscle thickness was close to being significantly larger in the LST than NHL (\(p = 0.050\))
Table 5.3. Comparison of changes to biceps femoris muscle architecture between training groups.

<table>
<thead>
<tr>
<th>Architecture variable</th>
<th>CON</th>
<th>NHL</th>
<th>LST</th>
<th>ANCOVA results (group)</th>
<th>Post-hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre Post</td>
<td>Pre Post</td>
<td>Pre Post</td>
<td>Pre Post</td>
<td></td>
</tr>
<tr>
<td>MT [cm]</td>
<td>2.20 ± 2.20</td>
<td>2.19 ± 2.33</td>
<td>2.36 ± 2.57</td>
<td>&lt;0.001</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>0.48 0.42</td>
<td>0.40 0.35</td>
<td>0.41 0.36</td>
<td>0 0</td>
<td>0</td>
</tr>
<tr>
<td>PA [°]</td>
<td>13.0 ± 13.1</td>
<td>13.3 ± 13.1</td>
<td>13.1 ± 13.0</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>3.4 3.8</td>
<td>3.40 2.2</td>
<td>4.5 2.2</td>
<td>.998</td>
<td>0</td>
</tr>
<tr>
<td>FL [cm]</td>
<td>9.87 ± 9.56</td>
<td>9.91 ± 10.14</td>
<td>9.93 ± 8.50</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>1.99 1.59</td>
<td>2.32 2.06</td>
<td>2.50 2.14</td>
<td>.850</td>
<td>8</td>
</tr>
</tbody>
</table>

CON–control group; NHL–Nordic hamstring lowers group; LST–lengthened-state training group; MT–muscle thickness; PA–pennation angle; FL–fascicle length; $\eta^2_p$=partial eta squared; $\beta$ = observed power. Significant P-values (P < .05) are shown in bold.

Figure 5.4. Comparison of change in muscle thickness (adjusted for pre-training measurements) across training groups; *– significant difference from CON.

The eccentric peak torque measured during isovelocity (50°/s) knee flexion testing at pre- and post-training measurement sessions are presented in Table 5.4 and Figure 5.5. A
group effect ($p = < 0.001$) was observed after adjustment for pre-training measures. Post-hoc pairwise comparisons showed that the change in eccentric peak torque was larger than that of the CON group in the NHL (+7.4%) and LST (12.6%). The adjusted change was also larger in the LST than NHL.

**Table 5.4.** Comparison of changes to hamstrings eccentric strength between training groups.

<table>
<thead>
<tr>
<th></th>
<th>CON</th>
<th>NHL</th>
<th>LST</th>
<th>ANCOVA results (interaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>125.8</td>
<td>142.5</td>
<td>153.0</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Post</td>
<td>123.5</td>
<td>150.0</td>
<td>157.2</td>
<td>$0.711$ $0.001$</td>
</tr>
<tr>
<td>EccPT [Nm]</td>
<td>± 37.1</td>
<td>± 46.0</td>
<td>± 48.7</td>
<td>$1.000$ $&lt; 0.001$ $0.711$</td>
</tr>
<tr>
<td>Post-hoc</td>
<td>ΔNHL &gt; ΔCON,</td>
<td>ΔLST &gt; ΔCON,</td>
<td>ΔNHL &gt; ΔLST</td>
<td></td>
</tr>
</tbody>
</table>

CON—control group; NHL—Nordic hamstring lowers group; LST—lengthened-state training group; EccPT—eccentric peak torque; $\eta^2_p$—partial eta squared; $\beta$ = observed power. Significant P-values ($P < .05$) are shown in bold.

**Figure 5.5.** Comparison of change in eccentric peak torque (adjusted for pre-training measurements) across training groups; *—significant difference from CON; †—significant difference from NHL.
5.4 Discussion

The main purpose of this study was to determine the architectural and functional adaptations of the hamstrings following two different 12-week eccentric training programme when compared to a control group. The main finding of the study was that following NHL and LST training, the biceps femoris became thicker. However, this increase in muscle thickness was not accompanied by changes to muscle pennation angle or fascicle length. In a previous investigation reporting a similar lack of change to biceps femoris fascicle length following a 6-week NHL training programme, it was suggested that findings could be due to the absence of an elevated training surface which resulted in the muscle being trained at shorter lengths (Seymore, Domire, DeVita, Rider & Kulas, 2017). However, the use of a custom-built elevated rig in this study produced similar results which suggests that extending the range of motion of the NHL may not be sufficient for eliciting positive changes to muscle fascicle length. However, there is evidence to suggest that NHL training can increase biceps femoris fascicle length with increment values of up to 24% recently reported (Bourne et al., 2017). This increase in muscle fascicle length as a result of sarcomerogenesis could possibly be one of the mechanisms responsible for the reduction in injury risk after a NHL training programme; as it has been suggested that longer fascicles may be more resistant to overstretching and damage caused by powerful eccentric contractions which occur during sprinting movements (Brockett, Morgan & Proske, 2004). The absence of observed changes to biceps femoris fascicle length in this study for both exercises could be partly explained by the large variability associated with the measurement of fascicle length, evidenced by the relatively large standard deviation in change data (10–24%). Another possible explanation is that as the ultrasound method utilised provides two-dimensional information, changes in muscle fascicle length in unmeasured planes could be unaccounted for.
The increases in muscle thickness after NHL and LST training suggest that hypertrophy had occurred at the measurement site (mid part of muscle). However, it has been found that changes in muscle thickness and anatomical cross-sectional area following different resistance training programmes are variable along the muscle body (Blazevich, Cannavan, Coleman & Horne, 2007). As the ultrasound measurement was only taken at one site, it is possible that response (in terms of hypertrophic tendency) to resistance training was high at the chosen site. Therefore, it is important to consider the assessment of muscle volume, which could be further investigated through the use of magnetic resonance imaging of the whole muscle in order to fully observe the hypertrophic effects of resistance training interventions. Nonetheless, the results of this study suggest that muscle hypertrophy could have occurred.

Previous published literature (Timmins et al., 2015) and results from the preceding chapter of this thesis (Chapter 3) have found that reduced fascicle length is associated with an increase in muscle pennation angle. It was postulated that these changes negated the effects of any changes to muscle thickness (Timmins et al., 2015). However, in this study, changes to muscle thickness were still observed despite the lack of changes to both fascicle length and pennation angle. This suggests that the relationship between the commonly assessed muscle architecture variables may not be completely correlational with underlying mechanisms modulating changes in either variable. Further investigations, possibly through modeling studies, are required to understand other contributory factors to changes in muscle architecture.

Another finding of this study was that after NHL and LST training, eccentric strength increases through peak torque generated was larger than participants who did not undergo either training programme. This suggests that both training programmes are effective in increasing eccentric hamstring strength. Further comparisons also suggest that the LST could
be a more effective training programme than the NHL due to the larger increase in eccentric strength reported. However, it is important to acknowledge that in the present study, isoveLOCITY contractions were performed at a relatively slow velocity (50°/s) which may not be fully representative of the high angular velocities attained during high-speed running (up to 1000°/s; Kivi, Maraj & Gervais, 2002). However, Higashihara and colleagues (2010) had previously found no differences in knee flexion peak torque between a much higher velocity of 300°/s and 60°/s, suggesting that the results of the isoveLOCITY strength measures in this study could be interpreted with good external validity.

The exact underlying mechanism for the higher increases in eccentric strength following LST compared to NHL are unknown. However, it is possible that based on the results of the preceding chapter (4) which looked at muscle activation characteristic of various hamstring strengthening exercises including the NHL and LST, the high BF activity and muscle elongation of the LST exercise during end-ROM may be a reason for its higher efficacy as a hamstring strengthening exercise (especially during eccentric movements). This could be attributed to it being a more injury-mechanism specific training intervention.

It was also interesting to note that eccentric strength variations between groups were larger than the architectural variations. This seems to suggest that besides the muscle architecture features measured, there may be other underlying mechanisms driving the increases in strength. By utilising EMG as a measure of efferent neural drive changes, some studies have found that resistance training is effective in increasing overall muscle activity (Daglas et al., 2013), which may help understand the findings reported in this study. In a more recent study investigating agonist neural drive and hypertrophy of the quadriceps in relation to strength gains pre and post isometric training, it was suggested that these factors combined to explain the majority of variance (approximately 60%) in strength changes (Balshaw, 2017). The adaptation in neural drive as a mechanism underlying strength change
observed in this study is further substantiated in a recent conducted by Maeo and colleagues (2018) who found that eccentric training induces greater neuromuscular changes within the quadriceps than concentric training, with changes in EMG activity accounting for between 53-80% of strength changes. Therefore, it would be beneficial for explaining the role of neural adaptations in the changes observed in this study if future work could investigate this similar relationship (neural drive and strength increase) within the hamstrings.

There were some limitations to this study. Although muscle architecture (especially hypertrophic measures) are associated with muscle strength, it is not the sole determinant. Another major determinant of muscle strength is neural drive (Folland & Williams, 2007) which was not measured in this study through the use of electromyography. It is possible that the increases in eccentric strength measured in this study were the result of the relationship between changes to muscle architecture and neural drive. Further studies should consider these two factors in tandem as part of the study design in order to better understand the mechanisms underlying found strength increases. In addition, the exercise utilised in the LST programme cannot be performed without a concentric phase. Therefore, in order to reduce the effect of a prior concentric contraction on the subsequent eccentric contraction, participants were assisted through the concentric phase whenever possible and instructed to perform the concentric phase as quickly as possible. It is possible that this had an effect on the eccentric strengthening of the hamstrings although it is likely due to the phenomenon training-specificity (Seger, Arvidsson & Thorstensson, 1998; Tomberlin et al., 1991).

In summary, the present study sought to evaluate the effectiveness of an LST intervention when compared to a control group and a group performing the commonly prescribed NHL. It was found that both exercises were effective in inducing positive changes to biceps femoris muscle thickness; and the LST was more effective at increasing eccentric hamstring strength than the NHL. This suggests that the LST could be a more effective
prophylactic exercise in reducing HSI risk. Future prospective training studies could utilise LST to understand its effect on the prevalence of HSI among athletes in order to establish evidence for its efficacy.
Chapter 6: General Discussion

6.1 Introduction

A hamstring strain injury is a common and problematic muscular injury that affects athletes at both professional and sub-elite levels from a wide range of sprint-based sports, especially those that involve repeated bouts of high-speed running/sprinting (Brooks, Fuller, Kemp & Reddin, 2005; Orchard, James & Portus, 2006). The challenge associated with addressing HSIs is further exacerbated by the high recurrence rates of injury which in most cases, are more severe than the initial injury (Koulouris, Connell, Brukner & Schneider-Kolsky, 2007), requiring an extended period of rehabilitation and recovery (Koulouris et al., 2007). It has also been established that there is a substantial cost to both individual and organisations as a consequence of injury (Hickey et al., 2013).

Thus, it is important to address the prevalence of HSI through a systematic approach by first understanding the modifiable risk factors of injury (e.g. muscle structure and function) and evaluating the design of strengthening programmes with consideration of how the injury occurs in the first instance. Currently, approaches to designing hamstring strengthening exercises have focused on utilising eccentric training due to the strong evidence suggesting that eccentric strength weakness (Brockett et al., 2004) is a major contributory risk factor to HSIs. As a result, there have been a number of investigations into the efficacy of eccentric strengthening exercises, of which, the Nordic hamstring lowers (NHL) has received considerable attention. This has led to it being included as part of the FIFA 11+ strengthening programme, further adding to its acceptance as the ‘gold standard’ in hamstring strengthening exercises, especially among football players. As a result, a large body of literature has been skewed towards understanding the efficacy of the NHL (Arnason et al., 2008; Brito et al., 2010; Clark et al., 2005). However, by comparing information
from elongation stress quantifications (Guex & Millet, 2013), it can be observed that
commonly prescribed hamstring-strengthening exercises including the NHL are not
performed under muscle length conditions representative of the state of the muscle during the
onset of injury. In the author’s opinion, a variation of exercise position of many common
exercises (e.g. increasing the amount of hip flexion to induce a lengthened-state of the
hamstrings) could prove to be more effective in strengthening the hamstrings in relation to
reducing the risk of injury.

Therefore, the purpose of the series of experimental studies conducted in project was
to understand the risk factors associated with HSIs and examine the characteristics of
different hamstring strengthening exercises that are commonly prescribed. Another purpose
of this study was to understand how an intervention designed to address injury-mechanism
related parameters (e.g. weakness in eccentric strength at longer muscle lengths) can reduce
the risk of sustaining HSI. In order to meet the purposes of this research study, three separate
experimental studies were designed and conducted.

Firstly, a comparative study was conducted to examine differences in muscle structure
and function between previously-injured and un-injured athletes; while assessing the
reliability of muscle architecture and visco-elastic property measures. A second cross-sectional
study was conducted to examine the muscle activation characteristics of commonly
prescribed and variations of these exercises (i.e. exercises modified to be executed at longer
muscle lengths). Finally, based on the results of the second study, the efficacy of an
experimental exercise involving lengthened-state training (LST) was compared to a control
group and NHL training group after a 12-week training period.

Based on the results of the first study, the muscle architecture and structural risk
factors of HSI could be identified; with characterisations of the hamstrings in previously-
injured individuals, together with muscle function allowing for this determination. The results
of the second study would serve to provide information on how different commonly
prescribed and variations of exercises activate the hamstrings differently; by allowing the
identification of a suitable exercise to be used in a subsequent training study. By utilising the
results of both studies, the third study could subsequently be designed to address the efficacy
of the proposed training intervention by observing its effects on some of the risk factors
identified from the first study.

6.2 Conclusion

Details of main findings of this research project were reported within the respective
chapters:

(i) Chapter 3 - Hamstring structural and functional differences between previously-
    injured and -uninjured athletes.

(ii) Chapter 4 - Muscle activation characteristics across different hamstring strengthening
    exercises.

(iii) Chapter 5 - Architectural and functional adaptations of hamstrings following a 12-
    week lengthened-state training programme

This section will summarise the findings from the aforementioned chapters in order to
address the objectives of this research project.

1. Comparison of muscle structure and functional differences between previously-
    injured and -uninjured athletes:

   a. Architecture: The previously-injured limb (IL) was characterised by
      larger pennation angle and shorter fascicle length on the biceps femoris (BF);
      with similar measurements of muscle thickness between the IL, un-injured
limb (UL) and control limb (CL). Muscle architecture measures on the semitendinosus (ST) were similar between all limbs.

b. **Visco-elastic property:** BF was found to be stiffer on the IL than UL. No differences were pronounced in the comparison of decrement or oscillation frequency measures.

c. **Knee flexor strength:** IL was associated with weaker knee flexor isometric strength at longer muscle lengths compared to CL and UL. Concentric strength measures of peak torque were similar between limbs eccentric peak torque (EccPT) measured was lower in the IL than both CL and UL during isovelocity strength assessment at 60°/s. EccPT also occurred at the more knee flexed position in the IL compared to UL.

d. **Sprinting kinematics:** Peak hip flexion angle was observed to be higher in the IL compared to UL during the late-swing phase of sprinting.

2. **Characterisation of muscle activation across different hamstring strengthening exercises.**

   a. **Muscle activation across range of exercise movement:** Muscle activation was different across the three 15° sectors preceding the termination of exercise in a progressive manner.

   b. **Muscle activation in final sector:** Muscle activation in the final sector was highest in the NHL for both BT and ST. Considerably high activation of the BF was found during the seated-leg curl with hip flexion exercise (SLC).

   c. **Elongation stress:** SLC exhibited the highest elongation stress while this measure was the lowest during the NHL.

3. **Evaluation of a 12-week lengthened-state training programme (LST) compared to a control (CON) and Nordic hamstring lowers (NHL) training group.**
a. Muscle architecture: Participants from both NHL and LST groups exhibited higher muscle thickness compared to the CON group. Pennation angle and fascicle length measures were similar between groups.

b. Eccentric strength: Both NHL and LST showed improvements in eccentric strength compared to the CON group, with the LST demonstrating larger strength increases compared to the NHL.

6.3. Overall summary

To the author’s knowledge, this was the first comprehensive study on HSI encompassing both identification of risk factors and a subsequent intervention programme to examine exercise-induced changes to these factors. The results of the empirical findings suggest that a large volume of work is still required to fully understand the mechanisms underlying the risk factors of HSI, especially structural risk factors of the muscle. The inherent difficulty in being able to fully understand the risk factors of injury lies in the need to examine individuals who have previously sustained an injury. This limits studies looking at comparative differences between previously-injured and -uninjured muscles to be retrospective in nature. Due to this design limitation, current published literature and the findings of this study can only determine an association between measured variables and injury risk. The challenge lies in establishing if these deficits in measurements of variables may potentially result in the onset of injury or had occurred as a result of the injury. Based on findings of the first study of this thesis, shorter fascicles and larger pennation angle has been found in previously-injured hamstrings which is supported by previous investigations (Timmins et al., 2015). Future studies should consider examining these muscle architecture variables, together with muscle function variables, in athletes by utilising a prospective design approach (i.e. determining associations between these variables before and after the
onset of injury). Although this presents a difficult undertaking due to the nature of the study, the results of such an investigation will provide invaluable information relating to fully understanding the risk factors of injury. At present, it is hoped that the results of this study can contribute towards developing valid testing protocols for screening of athletes that are evidenced by research. Athletes and coaches can also be better informed on how to accurately assess one’s susceptibility to hamstrings injury through the formulation of a set of assessment standards to determine injury risk.

The findings of this study also suggest that although many hamstring strengthening exercises such as the NHL are aligned with existing literature on the mechanisms of HSIs (Heiderscheit et al., 2015; Schache et al., 2012) through the emphasis on eccentric training, they do not fully function during the state of the muscle when it typically gets injured (Chumanov et al., 2012). In the second study, the author postulated that since HSIs occur when the hamstring muscle is lengthened and eccentrically contracted, it might be useful to strengthen the muscle while it is in a lengthened state. By making simple adjustments to hip flexion angle while performing commonly prescribed exercises, it was found that substantially high levels of BF activation were accompanied by high elongation stress of the muscle were exhibited. This was most prevalent in the seated-leg curl performed with hip flexion. The NHL, on the other hand, demonstrated the lowest elongation stress during its execution suggesting that although high activations of the BF were found, it does not appropriately activate the muscle in the correct state. The main implication of this finding is that although strong evidence exists for advocating the use of NHL, it may not be the most effective exercise. This should be viewed in tandem with the difficulty in implementing NHL during the early stages of rehabilitation (due to the high eccentric loading) which warrants the need for a better intervention. Based on the findings from this study, it was hypothesised and
tested in a further investigation that LST may be more effective than NHL in reducing HSI risk.

After 12-weeks of supervised training, it was found that both the LST and NHL produced increases in muscle thickness and eccentric strength. This provides further evidence that an eccentric training is able to produce substantial increases in strength measures. Interestingly, the LST was found to be more effective at increasing eccentric strength than the NHL. This provides preliminary evidence for the use of lengthened-state training in reducing the risk of HSI. More importantly, it presents that research into development of strengthening programmes should consider both muscle contraction type and muscle length specific to the type of injury it is designed to prevent or rehabilitate. For sporting bodies, the knowledge gathered would aid in the improvement and development of training programmes for athletes, such as implementing appropriate training methods to minimise the risk of HSIs.

Future research should consider utilising large-scale prospective studies with a focus on muscle structure and function variables to provide strong evidence for the risk factors of injury. With this information, studies investigating the efficacy of interventions could be directed towards understanding how experimental training methods can positively modify these risk factors. Further comprehensive work is also required to establish the importance of training the muscle in a lengthened-state when utilising prophylactic exercises targeted at reducing strain injuries. This could be accomplished by conducting controlled studies (i.e. investigating the effects of LST and non-lengthened state training on the contralateral limbs of an individual). Additionally, although a 12-week training period is relatively long when compared against similar studies, it would be useful to understand the effects of LST over a longer training period and consider the detraining effects associated. It is hoped that through the results of this study, involved stakeholders such as the athlete and relevant sporting organisations would be able to adopt a new perspective in the development of training
programmes. This new perspective should include first identifying the prevalent injuries present in the sport, followed by a scientific approach to understanding how these injuries occur (e.g. muscle sites affected, moment of onset of injury and state of muscle during injury). Subsequently, an evidence-based approach could be adopted to strengthen the muscle, or in the case of an injury, rehabilitate the muscle to restore function.

In summary, the author hopes that the results of this study could serve as the foundation for a new approach towards the development of hamstring strengthening exercises.
References


Lawrence Earlbaum Associates.


Leonard, C., Deshner, W., Romo, J., Suoja, E., Fehrer, S., & Mikhailenok, E. (2003). Myotonometer Intra- and Interrater Reliabilities11A commercial party with a direct financial interest in the results of the research supporting this article has conferred or will confer a financial benefit upon one or more of the authors. *Archives of Physical Medicine and Rehabilitation, 84*(6), 928-932.


Appendix 1

NTU INSTITUTIONAL REVIEW BOARD Approval
Project Title: Hamstring Muscle Structural and Functional Differences Between Previously-injured and Uninjured Athletes

I refer to your application for ethics approval with respect to the above project.

The Board has deliberated on your application and noted from your application that your research involves collecting behavioral data from participants through a series of strength tests.

You have also confirmed that informed consent will be obtained from the participants and you have guaranteed the confidentiality of your participants' biodata obtained from them.

The documents reviewed are:

a) NTU IRB application form dated 28 April 2015
b) Participant information sheet and consent form: version 1 dated 28 April 2015
c) Data collection form: version 1 dated 28 April 2015

The Board is therefore satisfied with the bioethical consideration for the project, and approves the ethics application under Expedited review. The approval period is from 07 May 2015 to 31 March 2018. The NTU IRB reference number for this study is IRB-2015-02-005. Please use this reference number for all future correspondence.

The following protocol and compliances are to be observed upon NTU IRB approval:

1. All research involving procedures greater than minimal risk on minors (individuals who are less than the legal age of 21 years old) requires IRB approved written Parental Consent and assent from the participant to be obtained before any research protocols can be administered. Minimal risk refers to an anticipated level of harm and discomfort that is no greater than that ordinarily encountered in daily life, or during the performance of routine educational, physical, or psychological examination.

2. Only the approved Participants Information Sheet and Consent Form should be used. It must be signed by each subject prior to initiation of any protocol procedure. In addition, each subject should be given a copy of the signed consent form.
Appendix 2

Darren Nin

From: ssehs res ent
Sent: Tuesday, November 15, 2016 9:10 PM
To: Jonathan Folland
Cc: Darren Nin
Subject: Ethical Clearance

Dear Dr Folland,

Reference number SSEHS-2098

I can confirm that your ethics checklist:

Muscle activation characteristics of different hamstring strengthening exercises

Has been approved. The reference number is SSEHS-2098

Kind regards

Charlotte Barradell
Finance and Research Office, J80.1G
School of Sport, Exercise and Health Sciences
Loughborough University
Loughborough
Leicestershire LE11 3TU
Tel: +44 (0) 1509 226416

Loughborough University

Athena SWA
Silver Award
Appendix 3

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25 April 2017

Associate Professor Kong Pul Wei
National Institute of Education

NTU INSTITUTIONAL REVIEW BOARD APPROVAL

Project Title: Muscle activation characteristics of different hamstring strengthening exercises
(Grant Approved: SGD559,495; to be funded by A*STAR Tier 1 program)

I refer to your application for ethics approval with respect to the above project.

The Board has considered your application and noted from your application that your research involves collecting behavioral data from participants through physical tasks.

You have also confirmed that informed consent will be obtained from the participants and you have guaranteed the confidentiality of your participants' biodata obtained from them.

The documents reviewed are:

a) NTU IRB application form dated 19 January 2017
b) Participant information sheet and consent form: version 2 dated 13 April 2017
c) Data collection form: version 2 dated 13 April 2017

The Board is therefore satisfied with the ethical consideration for the project and approves the ethics application under Full Board review. The approval period is from 25 April 2017 to 24 April 2018. The NTU IRB reference number for this study is IRB-2017-C1-020. Please use this reference number for all future correspondence.

The following protocol and compliances are to be observed upon NTU IRB approval:

1. All research involving procedures greater than minimal risk on minors (individuals who are less than the legal age of 21 years old) requires IRB approved written Parental Consent and assent from the participant to be obtained before any research protocols can be administered. Minimal risk refers to an anticipated level of harm and discomfort that is no greater than that ordinarily encountered in daily life, or during the performance of routine educational, physical, or psychological examination.

2. Only the approved Participant Information Sheet and Consent Form should be used. It must be signed by each subject prior to initiation of any protocol procedures. In addition, each subject should be given a copy of the signed consent form.

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Appendix 4

Dear Darren,

Many thanks for your response to the Sub-Committee's conditional approval. On behalf of the Sub-Committee, I can confirm that the conditions of approval for the study have now been met and that the study R17-P054 now has full ethical approval.

If in the future you wish to make any amendments to the study, you should contact me in the first instance quoting the reference number above.

This approval applies until 30 August 2017. If the study continues beyond this date you should submit a request for an extension.

Kind Regards,

Jackie

Jacqueline Green
Secretary, Ethics Approvals (Human Participants) Sub-Committee
Hauser Building, Research Office
Loughborough University
01509 222423
J.A.Green@lboro.ac.uk
Website: http://www.lboro.ac.uk/committees/ethics-approvals-human-participants/

From: Darren Nin
Sent: Monday, March 20, 2017 11:40 PM
To: Darren Nin
Subject: FW: HPSC Research Proposal R17-P054

Hi Jackie
Appendix 5

IRB-2017-07-030

12 September 2017

Associate Professor Kong Pui Wah
National Institute of Education

NTU INSTITUTIONAL REVIEW BOARD APPROVAL:

Project Title: Effect of lengthened-state eccentric training on hamstring function and structure

Amount Approved: SGD555,196; to be funded by N/E AERF grant.

I refer to your application for ethics approval with respect to the above project.

The board has considered your application and noted from your application that your research involves collecting behavioral data from participants through performing some physical activities.

You have also confirmed that informed consent will be obtained from the participants and you have guaranteed the confidentiality of your participants’ identities obtained from them.

The documents reviewed are:

a) NTU IRB application form dated 06 September 2017
b) Participant Information sheet and consent form: version 1 dated 06 September 2017
c) Data collection form: version 1 dated 06 September 2017

The Board is therefore satisfied with the bioethical consideration for the project and approves the ethics application under Full Board review. The approval period is from 12 September 2017 to 31 August 2018. The NTU IRB reference number for this study is IRB-2017-07-030. Please use this reference number for all future correspondence.

The following protocol and compliance are to be observed upon NTU IRB approval:

1. All research involving procedures greater than minimal risk on minors (individuals who are less than the legal age of 21 years old) requires IRB approved written Parental Consent and assent from the participant to be obtained before any research protocols can be administered. Minimal risk refers to an anticipated level of harm and discomfort that is no greater than that ordinarily encountered in daily life, or during the performance of routine educational, physical, or psychological examination.

2. Only the approved Participant Information Sheet and Consent Form should be used. It must be signed by each subject prior to initiation of any protocol procedures. In addition, each subject should be given a copy of the signed consent form.

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Appendix 6

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRES

IPAQ: SHORT LAST 7 DAYS SELF-ADMINISTERED FORMAT

FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health-related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken in 12 countries (14 sites) across 6 continents during 2000. The final results suggest that those measures have acceptable measurement properties for use in many settings and in different languages. IPAQ is suitable for use in regional, national and international monitoring and surveillance systems and for use in research projects and public health program planning and evaluation. International collaboration on IPAQ is on-going and an international prevalence study is under development.

Using IPAQ

Worldwide use of the IPAQ instruments for monitoring and research purposes is encouraged. It is strongly recommended, to ensure data quality and comparability and to facilitate the development of an international database on health-related physical activity, that:

- no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments,
- if additional questions on physical activity are needed they should follow the IPAQ items,
- translations are undertaken using the prescribed back translation methods (see website)
- new translated versions of IPAQ be made available to others via the web site to avoid duplication of effort and different versions in the same language,
- a copy of IPAQ data from representative samples at national, state or regional level be provided to the IPAQ data storage center for future collaborative use (with permission) by those who contribute.

More Information

Two scientific publications presenting the methods and the pooled results from the IPAQ reliability and validity study are due out in 2002. More detailed information on the IPAQ process, the research methods used in the development of the IPAQ instruments, the use of IPAQ, the published papers and abstracts and the on-going international collaboration is available on the IPAQ web-site.

www.ipaq.ki.se

This is the final SHORT LAST 7 DAYS SELF-ADMINISTERED version of IPAQ from the 2000-01 Reliability and Validity Study. Completed May 2001.
INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

IPAQ: SHORT LAST 7 DAYS SELF-ADMINISTERED FORMAT

FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS

NOTE: EXAMPLES OF ACTIVITIES MAY BE REPLACED BY CULTURALLY RELEVANT EXAMPLES WITH THE SAME METS VALUES (SEE AINSWORTH ET AL., 2000).
INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. This is part of a large study being conducted in many countries around the world. Your answers will help us to understand how active we are compared with people in other countries.

The questions are about the time you spent being physically active in the last 7 days. They include questions about activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Your answers are important.

Please answer each question even if you do not consider yourself to be an active person.

THANK YOU FOR PARTICIPATING.

In answering the following questions,

- **vigorou**s physical activities refer to activities that take hard physical effort and make you breathe much harder than normal.

- **moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.
1a. During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, digging, aerobics, or fast bicycling?

Think about only those physical activities that you did for at least 10 minutes at a time.

_______ days per week

1b. How much time in total did you usually spend on one of those days doing vigorous physical activities?

or

_______ hours ______ minutes

☐ none

2a. Again, think only about those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

_______ days per week

2b. How much time in total did you usually spend on one of those days doing moderate physical activities?

or

_______ hours ______ minutes

☐ none

3a. During the last 7 days, on how many days did you walk for at least 10 minutes at a time? This includes walking at work and at home, walking to travel from place to place, and any other walking that you did solely for recreation, sport, exercise or leisure.

_______ days per week

3b. How much time in total did you usually spend walking on one of those days?

or

_______ hours ______ minutes

☐ none

The last question is about the time you spent sitting on weekdays while at work, at home, while doing course work and during leisure time. This includes time spent sitting at a desk, visiting friends, reading, traveling on a bus or sitting or lying down to watch television.

4. During the last 7 days, how much time in total did you usually spend sitting on a week day?

_______ hours ______ minutes

This is the end of the questionnaire, thank you for participating.
Appendix 7

Health Screen Questionnaire for Study Volunteers

As a volunteer participating in a research study, it is important that you are currently in good health and have had no significant medical problems in the past. This is (i) to ensure your own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm your fitness to participate:

Please place a tick (√) in the box which best represents your answer to each question.

1. At present, do you have any health problem for which you are:
   (a) experiencing pain or discomfort................. [Yes] [No]
   (b) on medication, prescribed or otherwise........ [Yes] [No]
   (b) attending your general practitioner............ [Yes] [No]
   (c) on a hospital waiting list......................... [Yes] [No]

2. In the past 6 months, have you had any injuries to your:
   (a) back or legs requiring more than 7 days' rest.... [Yes] [No]
   (a) arms requiring more than 7 days' rest........... [Yes] [No]

2. In the past two years, have you had any illness or injury which required you to:
   (a) consult your GP..................................... [Yes] [No]
   (b) attend a hospital outpatient department........ [Yes] [No]
   (c) be admitted to hospital......................... [Yes] [No]

3. Have you ever had any of the following:
   (a) Convulsions/epilepsy............................... [Yes] [No]
   (b) Asthma............................................... [Yes] [No]
   (c) Eczema............................................... [Yes] [No]
   (d) Diabetes............................................. [Yes] [No]
   (e) A blood disorder................................... [Yes] [No]
   (f) Head injury.......................................... [Yes] [No]
   (g) Digestive problems............................... [Yes] [No]
   (h) Heart problems/chest pains.................... [Yes] [No]
   (i) Problems with muscles, bones or joints...... [Yes] [No]
   (j) Disturbance of balance/co-ordination........ [Yes] [No]
   (k) Numbness in hands or feet.................... [Yes] [No]
   (l) Disturbance of vision.............................. [Yes] [No]
(m) Ear hearing problems ................................................................. Yes [ ] No [ ]
(n) Thyroid problems ................................................................. Yes [ ] No [ ]
(o) Kidney or liver problems ................................................................. Yes [ ] No [ ]
(p) Problems with blood pressure ................................................................. Yes [ ] No [ ]

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)

4. Smoking and family history

(a) Are you a current or recent (within the last six months) smoker? Yes [ ] No [ ]
(b) Has any member of your family under 35 died suddenly during or soon after exercise? Yes [ ] No [ ]

5. Allergy Information

(a) Are you allergic to plasters? Yes [ ] No [ ]
(b) Are you allergic to latex? Yes [ ] No [ ]

If YES to any of the above, please provide additional information on the allergy

6. Are you currently involved in any other research studies at the University or elsewhere? Yes [ ] No [ ]

If yes, please provide details.

7. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name ........................................................................................................

Telephone Number ................................................................................

Work [ ] Home [ ] Mobile [ ]

Relationship to Participant ........................................................................
8. GP Contact Details

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**Participant Code:**

- **Set 1**
  - Completed Y/N
  - Load (kg)
- **Set 2**
  - Completed Y/N
  - Load (kg)
- **Set 3**
  - Completed Y/N
  - Load (kg)
- **Set 4**
  - Completed Y/N
  - Load (kg)

**Nordics**

**Signature**

**Date and Time**
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Week: 8
Session: @ 9 pm
Sets: 4
Reps: 10