LOWER LIMB MUSCLE ACTIVATION DURING SPRINTING AND HAMSTRING STRENGTH TRAINING EXERCISES: IMPLICATIONS FOR MITIGATING HAMSTRING INJURY RISK IN RUGBY UNION PLAYERS

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Declaration statement

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STATEMENT 1

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Abstract

Hamstring strain injuries (HSIs) are highly prevalent in sprinting-based sports, including rugby union, and have a high rate of recurrence, indicating the importance of injury prevention programmes. Exercise-based interventions are commonly used as a means of decreasing HSI incidence; however, the persistent injury rates suggests that current injury prevention practices could be improved. Comparing lower limb muscle activity during sprinting and hamstring exercises could improve exercise specificity and better inform exercise selection for training programmes aimed at minimising HSI risk. Therefore, the aim of this thesis was to examine the pattern and magnitude of lower limb muscle activation during sprinting and unloaded and loaded hamstring strength training exercises in rugby union players.

The first three studies were conducted with male players from an international rugby seven's team. Study 1 (Chapter 4) analysed the activity of biceps femoris long head (BFlh), semitendinosus (ST), gluteus maximus (GM), rectus femoris (RF) and medial gastrocnemius (MG) during the early stance and late swing phases of sprinting in international rugby seven's players (n = 5). No significant interactions or main effects were observed for peak muscle activity for sprint phase and muscle (all $p \geq 0.05$). A large ($d \geq 0.80$) and small mean difference ($d \leq 0.2$-0.49) was observed between BFlh and ST peak activity during early stance and late swing respectively, with higher BFlh activity relative to ST being observed. A significant main effect ($p \leq 0.001$) for integrated electromyography (iEMG) was observed for sprint phase only with higher iEMG occurring during the late swing phase compared to early stance, this was associated with a large effect size ($\eta^2 \geq 0.14$). Overall, there was a trend for higher BFlh activity during sprinting compared to ST which may contribute to the BFlh muscle's susceptibility to injury and the higher incidence of injury observed in the lateral hamstring.

Study 2 (Chapter 5) examined lower limb muscle activity during a series of hamstring strength training exercises including the Nordic hamstring exercise (NHE), single leg prone hamstring curl, single leg bridge, slider and single leg Roman chair hold (peak activity n = 7; iEMG n = 5). A significant interaction ($p \leq 0.05$), and a large effect size ($\eta^2 \geq 0.14$) for exercise and muscle was observed for all findings and significant main effects ($p \leq 0.05$) and large effect sizes ($\eta^2 \geq$ 0.14) for normalised peak activity were observed for exercise and muscle ($p \leq 0.05$) and co-

activation iEMG. Significantly greater BFlh and GM activity was observed completing the single leg Roman chair hold exercise with a weight-lifting bar when compared to using body weight only. The single leg Roman chair hold bar exercise generated the highest normalised iEMG and peak activity for BFlh and GM, with the peak activation exceeding the 100% reference value of sprinting. Collectively, BFlh activation was higher than ST during the majority of exercises and the highest ST peak and iEMG was generated during a single leg prone hamstring curl and single leg bridge exercises respectively. These findings suggest that these exercises could be considered for hamstring training programmes.

Study 3 (Chapter 6) investigated the relationship between muscle activation during different strength training exercises and sprinting (peak activity n = 7; iEMG n = 5). Limited significant relationships were observed for peak muscle activity and no significant findings were observed for iEMG; this was influenced by the small sample size. Biceps femoris long head activation during late swing and training exercises demonstrated a trend of positive relationships (peak activity r = 0.08 to 0.58; iEMG r = 0.02 to 0.65) while negative relationships were largely seen between BFlh activity during the early stance phase and exercises (peak activity r = -0.18 to -0.26; iEMG r = -0.08 to -0.57). The majority of exercises demonstrated positive relationships with sprinting for peak ST activity. The iEMG of ST during early stance showed a negative relationship with all exercises, while positive relationships were observed between ST iEMG during the late swing phase and all exercises. Overall, the findings demonstrated that hamstring muscle activity during the early stance and late swing phases of sprinting demonstrated stronger relationships with exercises that were not eccentrically biased.

Study 4 (Chapter 7) investigated the effect of load on lower limb muscle activation during hamstring strength training exercises in British University and College Sport (BUCS) rugby union players (n = 30). The exercises analysed included a double leg prone hamstring curl, single leg bridge and single leg Roman chair hold and three different loads were used for each exercise. The results for normalised peak activity and iEMG showed a significant interaction ($p \leq 0.001$) and a large effect size ($\eta^2 \geq 0.14$) for load and exercise, and exercise and muscle. Significant main effects ($p \leq 0.05$) were observed for muscle, exercise and load and all significant main effects were associated with large effect sizes ($\eta^2 \geq 0.14$). The majority of exercises generated a minimum of 70% of peak activity for the BFlh and ST muscles and ST activation was greater relative to BFlh during all exercises analysed. A continued increase in muscle activation in response to increased loading was observed during the double leg prone hamstring curl and single leg Roman chair. Loading did not however have a significant influence on muscle activation during the single leg bridge and it generated the highest peak BFlh and ST activity, with the medial hamstring reaching values in excess of 100%. Collectively, the findings illustrate the single leg bridge as the exercise of choice to generate high levels of BFlh and ST activity.

The findings of this thesis extend current knowledge regarding lower limb muscle activation during hamstring strength training exercises and the effect of load on activation relative to sprinting in rugby union players. To confirm the potential of the exercises identified in this thesis, additional research using different populations is necessary to further increase our understanding of hamstring activity during exercises and to better inform HSI prevention strategies.

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Completing this PhD has been an extremely challenging yet rewarding process. I am very grateful for the support that I have received from a number of people along the way and I would like to take this opportunity to acknowledge them.

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My final thanks go to my incredible husband and best friend, Andy. His love, support and encouragement has played a key part in my PhD journey. Thank you for your wisdom, patience, and unwavering confidence in me - I will always be grateful for you.

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Abbreviations

ANOVA	Analysis of variance
BF	Biceps femoris
BFlh	Biceps femoris long head
BFsh	Biceps femoris short head
EST	Early stance phase
fMRI	Functional magnetic resonance imaging
GM	Gluteus maximus
HD-EMG	High-density surface electromyography
HSI	Hamstring strain injury
HSIs	Hamstring strain injuries
iEMG	Integrated electromyography
LEDs	Light emitting diodes
LSW	Late swing phase
MG	Medial gastrocnemius
MTU	Musculotendon unit
MVIC	Maximal voluntary isometric contraction
NHE	Nordic Hamstring Exercise
nEMG	Normalised electromyography
niEMG	Normalised integrated electromyography
RF	Rectus femoris
SD	Standard deviation
sEMG	Surface electromyography
SENIAM	Surface electromyography for the non-invasive assessment of muscles
SM	Semimembranosus
ST	Semitendinosus

Chapter 1

Introduction

1.1 Overview

Hamstring strain injuries (HSIs) are a frequent occurrence in sports involving high-speed running and sprinting including football (Ekstrand *et al.*, 2016), track and field (Malliaropoulos *et al.*, 2012) and rugby union (Brooks *et al.*, 2005; 2006; Kenneally-Dabrowski *et al.*, 2019b), and are a common cause of absence from training and competition (Opar *et al.*, 2012; Wan *et al.*, 2017a) creating a considerable financial burden (Hickey *et al.*, 2014). A history of previous hamstring strain injury (HSI) increases the chance of experiencing a further injury by up 3.5 times (Hagglund *et al.*, 2006), and the time loss for recurrent HSI is significantly greater than for first time injury occurrence (Brooks *et al.*, 2006), thus emphasising the importance of primary injury prevention programmes. Ekstrand and co-workers (2016) report that HSI incidence remains elevated even though there has been increasing use of prevention programmes in the past two to three decades, suggesting that interventions have not been successful (Heiderscheit *et al.*, 2010) and the challenge of optimising the mitigation of injury risk and management of HSI remains.

Rugby union is a dynamic, collision team sport that involves repeated high intensity efforts, including tackling, kicking and running (Kenneally-Dabrowski *et al.*, 2019b). Hamstring strain injuries are the most common non-contact lower limb injury in rugby union (Brooks *et al.*, 2006) and a high prevalence of injury is reported in the sevens discipline (Rizi *et al.*, 2017), thus placing a great emphasis on the development of strategies to mitigate injury risk and injury management (Coughlan *et al.*, 2011; Williams *et al.*, 2013). High-speed running is an inherent element in rugby (Duthie *et al.*, 2006) and the HSIs observed are likely to be related to the running requirements of the sport as this is the most common mechanism for injury (Brooks *et al.,* 2006; Bourne *et al.*, 2015; Kenneally-Dabrowski *et al.*, 2019b).

Understanding the mechanisms of HSI is an important part of developing injury prevention strategies. While stretching and kicking are a cause of HSI (Brooks *et al.*, 2006; Askling *et al.*, 2000; 2006), the most common mechanism of injury is high-speed running and sprinting (Askling *et al.*, 2007; Brooks *et al.*, 2006; Yu *et al.*, 2017). There is a lack of consensus as to when the hamstrings are most vulnerable to injury. Some authors report that the risk of HSI is greatest during the early stance phase due to the ground reaction force resulting in high reaction forces at the hip and knee, which result in higher external joint moments compared to those which are present in late swing (Mann and Sprague, 1980; Yu *et al.*, 2008). Conversely, others argue that HSI occurs during the late swing phase as hamstring activity is at its highest, peak musculotendon force occurs and the musculotendon units (MTU) are at their longest length (Chumanov *et al.*, 2012; Schache *et al.*, 2012; 2013; Yu *et al.*, 2008). Recent work however, proposes that the transition between the late swing and early stance phases is the period where the risk of HSI is at its highest (Liu *et al.*, 2017; Sun *et al.*, 2015). Much of the evidence regarding muscle activity during high-speed running and sprinting is based on non-rugby populations, therefore an understanding of hamstring muscle activity during sprinting and the critical points in the gait cycle where the muscles are more susceptible to injury will offer further insight for the development of HSI prevention strategies in rugby.

The hamstring muscle complex includes the Biceps Femoris long head (BFlh), Biceps Femoris short head (BFsh), Semitendinosus (ST) and Semimembranosus (SM) muscles. Injury tends to occur in the biarticular muscles of the group, with the BFlh muscle being largely affected (Askling *et al.*, 2007; Kenneally-Dabrowski *et al.*, 2019b; Koulouris and Connell, 2003). Opinion regarding the vulnerability of the BFlh to injury includes the fact the muscle encounters the greatest stretch and strain during the late swing phase of high-speed running (Chumanov *et al.*, 2011; Higashihara *et al.*, 2016; Schache *et al.*, 2013) and that an alteration in the synergistic relationship of the BF and ST muscles, including differences in recruitment and activation, influences BFlh function (Schuermans *et al.*, 2014).

Sports injuries are complex and multi-factorial in nature, and models of injury aetiology illustrate how intrinsic and extrinsic risk factors might combine to predispose athletes to injury (Meeuwisse *et al.,* 2007). Extrinsic risk factors include environmental conditions while intrinsic factors are categorised as non-modifiable (such as age) and modifiable (such as muscle strength) factors. Recent literature expands on historic models of injury causality, describing how complex systems (Hulme *et al.,* 2015) incorporate external global factors such as the influence of regulations and regulatory agencies, organisations and professional bodies, along with individual intrinsic factors like age, previous injury, muscle strength, workload and neuromuscular control (Meeuwisse *et al.,* 2007) within a 'web of determinants' (Bitterncourt *et al.,* 2016).

A number of risk factors have been identified for HSI, including previous HSI (Best and Tietze, 2014; Koulouris *et al.*, 2007), shorter BFlh fascicle length (Timmins *et al.*, 2014; 2016a; 2017), reduced muscle strength (Lee *et al.*, 2018; Timmins *et al.*, 2016a), decreased hamstring strength-endurance (Freckleton et al., 2014; Schuermans *et al.*, 2016) and neuromuscular co-ordination (Sherry and Best, 2004; Schuermans *et al.*, 2014). As previous HSI has a significant influence on injury incidence and is a key predictor of future HSI, the need to address interventions that target modifiable risk factors are key as a means of minimising the risk of primary HSI occurrence. While it is difficult to identify the relative importance of each factor, it is likely that they will all interact as a 'web of determinants' (Bittencourt *et al.,* 2016).

Studies completed by Chumanov *et al.* (2007) and Schuermans *et al.* (2017a) identify the possible effect which the inter-muscular co-ordination of the lumbo-pelvic muscles has on the amount of strain experienced by the BF muscle during high-speed running. Reduced activity of GM increases the risk of HSI (Sugiura *et al.*, 2008) and recent work by Bramah and colleagues (2021) infers that altered activation of the gluteal muscles may negatively influence both hamstring and calf muscle injury risk. Collectively, these studies provide some insight into the role that muscle activity plays in HSI risk and how neuromuscular control and strength deficits may be addressed by focusing on muscle activation, all of which are modifiable risk factors. Consideration of the interactions of risk factors is required to address injury prevention programmes (Bittencourt *et al.,* 2016), for example, previous HSI has been shown to result in shorter fascicle length (Timmins *et al.,* 2014). While the influence of complex risk factor interaction on injury causality is acknowledged, the focus of this thesis is to analyse hamstring muscle activation during sprinting and hamstring training exercises to infer the possible benefit of specific exercises and loading patterns as part of mitigating HSI risk.

Hamstring strain injury incidence can be reduced via exercise-based interventions and hamstring strength is a common emphasis of research investigating injury prevention strategies, with eccentric exercise being a specific focus of interest (Askling *et al.*, 2013; Askling *et al.*, 2014; Peterson *et al.*, 2011). Training programmes incorporating exercises that require hamstrings to work at longer muscle lengths are influenced by evidence reporting lengthening of the hamstrings during the late swing phase of sprinting (Chumanov *et al.*, 2011; Schache *et al.*, 2012). Recently however, Hooren and Bosch (2017a; 2017b) have questioned whether muscle fascicles work eccentrically during late swing and rather suggest that they remain closer to an isometric action. While there is a lack of evidence for this opinion with regards to hamstring muscle activation during running, it requires some consideration and may influence exercise selection for hamstring training and mitigation of injury risk.

Biceps femoris long head and ST display long lengths and generate high activity during the early stance and late swing phases of running (Schache *et al.*, 2013), thus exercises which mimic these factors may be beneficial to prepare the hamstring muscles for the demands of sprinting and contribute to injury prevention strategies. High levels of muscle activation are required to yield muscular adaptations to training (Bourne *et al.*, 2018b). Agonist muscle activity is a function of load (Vigotsky *et al.*, 2015) and thus muscle activation and the specificity of exercises could be influenced by modifying the load applied to strength training exercises.

The coordination of the hamstrings with synergists and stabilisers of the hip and knee is necessary for sprinting (Schuermans *et al.*, 2017a; 2017b). The gluteus maximus (GM) stabilises the trunk during running (Liberman *et al.*, 2006), extends the hip through the stance phase and decelerates the thigh during late swing (Mann *et al.*, 1986; Schache *et al.*, 2010). Gastrocnemius is a biarticular muscle that plantar flexes the ankle and flexes the knee (Jonhagen *et al.*, 1996), and thus works in conjunction with the hamstrings at the knee joint. The quadricep muscles are the antagonists to the hamstring muscles, with the rectus femoris (RF) muscle being a biarticular muscle and thus acts in opposition to the hamstrings at the hip and the knee. Consequently, analysing the antagonistic activation of the RF may identify any indication of quadriceps dominance, which may influence the corresponding activation of the hamstring muscles (Best and Tietze, 2014). Collectively, it appears pertinent to consider these lower limb muscles to identify and determine their contribution to HSI and subsequent injury prevention programmes.

Surface electromyography (sEMG) is a tool frequently used in in the field of research as a means of analysing the behaviour of the neuromuscular system (Vigotsky *et al.*, 2018). In addition to the type of muscle contraction during hamstring exercises, there is a growing body of evidence using sEMG which shows non-uniform and selective activation of the hamstring muscles during strength training exercises (Bourne *et al.*, 2017a; Hegyi *et al.*, 2019a; Ono *et al.*, 2011). Analysing hamstring activity during sprinting and different exercises could contribute to the development of training programmes by identifying exercises which optimise muscle activation and demonstrate patterns of activity that mirror those of the injury risk phase of sprinting. Collectively, this would serve as a means of training the hamstrings for the demands of sprinting and subsequently aid the mitigation of HSI risk.

1.2 Aims and Objectives

In light of the existing evidence within the field of HSI based research and with a view to informing future hamstring injury prevention protocols, the aim of this thesis is to examine the activity of the hamstrings and synergistic muscles during the early stance and late swing phases of maximal velocity sprinting and hamstring strength training exercises in high-level rugby union players. This aim will be achieved via the following objectives:

Objective 1: Analyse and compare lower limb muscle activity during the early stance and late swing phases of the maximal velocity phase of sprinting.

Objective 2: Examine lower limb muscle activity during hamstring strength training exercises.

Objective 3: Examine the association between lower limb muscle activation during the early stance and late swing phases of the maximal velocity phase of sprinting and hamstring strength training exercises.

Objective 4: Establish the effect of load on lower limb muscle activation during hamstring strength training exercises.

1.3 Thesis organisation

The focus of this thesis is to further the understanding of hamstring muscle activation during sprinting and hamstring strength training exercises. Figure 1.1 provides a schematic diagram of the organisation of the thesis.

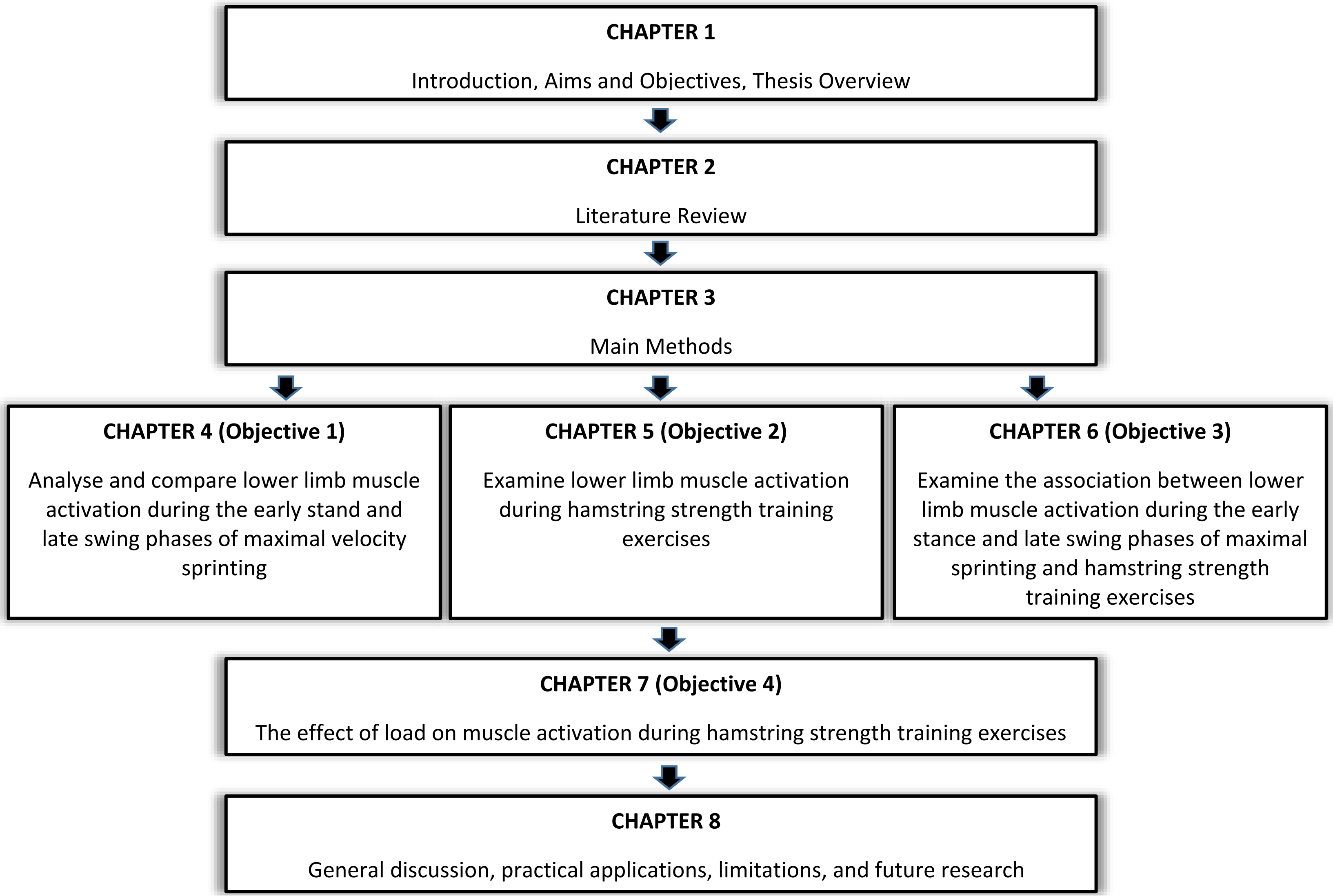

Figure 1.1 A schematic diagram illustrating the organisation of the thesis

Chapter 1 presents the overall theme of the thesis and establishes the aims and objectives of the research. Chapter 2 provides a review of literature pertaining to HSI injury incidence, mechanism of injury and lower limb muscle activity during sprinting. The chapter proceeds to provide a critical analysis of the research utilising kinematics and sEMG to investigate what phase of the sprinting gait cycle presents the greatest risk of HSI. Subsequently, critical discussion of research regarding HSI prevention and muscle activation patterns during hamstring strength training exercises is presented. Chapter 3 gives the detailed methodological procedures for the four studies in this thesis. Chapters 4 and 5 examined lower limb muscle activation during maximal velocity sprinting and hamstring strength training exercises respectively, with the two variables of interest being peak activation and integrated EMG (iEMG), the latter being a novel element of the research as it is a variable that does not appear in much of the existing literature. Chapter 6 utilised the data from the preceding two chapters to determine the relationship between hamstring activity during the early stance and late swing phases of sprinting and hamstring exercises. Chapter 7 investigates the effect of load on hamstring muscle activation during strength training exercises which, in chapter 6, demonstrated strong relationships with the activity observed during sprinting. Chapter 8 provides an overall discussion of the findings from the thesis and relevant practical applications. The limitations of the research are also discussed alongside suggested directions for future research.

1.4 Context of thesis

The idea and focus for this PhD thesis were born from a collaboration with the Welsh Rugby Union (WRU) sevens team, who due to several players experiencing HSIs, were looking at ways to train the hamstring muscles in more innovative ways as a means of addressing injury risk. In particular, the team were keen to investigate some of the more traditional hamstring strength training exercises with novel exercises focusing on isometric muscle contraction. The latter was in response to the emerging theory regarding isometric contraction of the contractile element of the hamstrings during the late swing of sprinting rather than eccentric muscle action (Van Hooren and Bosch, 2017a). The exercises investigated and protocol administered were chosen in discussion with practitioners working with the WRU. The elite level of participation and subsequent training and rugby schedule influenced the availability of players for data collection and testing protocols. Consequently, data collection took place on player recovery days and had to ensure the management of load and player safety, which was achieved by controlling the overall load that players were exposed to (i.e. total number of exercises and total number of repetitions).

The final study in this thesis recruited participants from Cardiff Metropolitan University first 15 a-side rugby team who are Welsh Rugby Union championship players. The inclusion of 15 a-side players compared to sevens players was based on the need to analyse a larger cohort of participants. The Cardiff Metropolitan University team had a less demanding training schedule compared to the international sevens rugby team, which allowed for more exposure to load and volume during data collection. With both cohorts, exercises were partly chosen based on current practice of each group. For instance, one of the exercises was a double leg prone hamstring curl which was completed using a conventional prone hamstring curl machine, compared to a single leg prone curl using an isokinetic dynamometer that was used when analysing the sevens players. The isokinetic dynamometer was chosen for the WRU participants as it is used by the practitioners for pre-season screening, load monitoring and return to play protocols. Conversely, the latter method, at the time of testing, was not adopted by the Cardiff Metropolitan University team. Collectively, the collaborative process ensured the research was embedded in real-world, applied settings and ensured that the coaches and participants were invested in the research.

Chapter 2

Literature Review

2.1 Introduction

Narrative reviews are commonly used as they provide a comprehensive means of covering the literature available on a specific topic (Jesson, Matheson and Lacey, 2011) and are an accepted and evident format used within the field of injury prevention and rehabilitation (Hamilton *et al.,* 2015; Kenneally Dabrowski *et al.,* 2019a; Roussiez and Van Cant, 2019; Shi *et al.,* 2020). This narrative approach is however often criticised for not following a specific set of rules for the search of evidence, as is the case with a systematic review, and thus lack the criteria to help mitigate potential bias (Collins and Fauser, 2005). The narrow focus of the research question and prescribed methods of a systematic review are reported as strengths of the approach, however it is also argued that these strengths may in turn be viewed as weaknesses as the method does not permit comprehensive coverage of a topic and available literature (Collins and Fauser, 2005; Jesson, Matheson and Lacey, 2011). It is also worth noting that a systematic review will not entirely eliminate bias; bias will need to be assessed, but there are many different tools available to do this, they are not usually supported by empirical evidence, different scales are used across tools leading to different conclusions regarding bias, and tools can include criteria not related to bias (Higgins *et al.,* 2011).

For the purpose of this thesis a narrative review was chosen to allow a comprehensive discussion and evaluation of literature (Jesson, Matheson and Lacey, 2011), which crossed a number of interlinking themes. This was viewed as the most optimal method to situate the current research project and to ensure the originality of the body of work being presented. It is acknowledged that the narrative review lacks explicit article selection criteria and thus can introduce selection bias, however, the more extensive survey and critical discussion of available literature achieved via the narrative method was considered the most suitable approach. While a systematic approach could have been adopted, to cover the broad range of topics included in the current narrative review would have required multiple systematic reviews. As systematic reviews can be burdeonsome (Collins and Fauser, 2005), it was considered a logical approach to conduct a single, broad and comprehensive narrative review as opposed to multiple systematic reviews. A narrative review allows for a more exploratory approach of the literature, and this also reflected the exploratory approach of the experimental work that follows in this thesis (i.e. rather than hypothesis driven research). The large body of literature covered in this review provides some confidence any selection bias has been generally avoided. Further the contents of the chapter were independently reviewed by three academics (Dr.Isabel Moore, Professor Jon Oliver and Dr. Craig Ranson) from diverse backgrounds (Biomechanics, Strength & Conditioning, Physiotherapy) and then amended by the author (Adeline Miles). This approach should have helped to reduce any information bias in review.

2.2 Hamstring strain injury

Hamstring strain injury is the most common muscle injury in sport (Mendiguicha *et al.*, 2012; Orchard and Seward, 2002; Woods *et al.*, 2004). The injury is described as an incident that causes acute posterior thigh pain that is confirmed clinically by a combination of pain with passive hamstring muscle stretch, pain and / or hamstring weakness, where direct external contact with the thigh is excluded as a cause of injury (Liu *et al.*, 2012; Opar *et al.*, 2012). Hamstring strain injuries account for up to 34% of all injuries reported in Australian rules football, rugby union, soccer, cricket and track sprinting (Brooks *et al.*, 2006; Hallen and Ekstrand, 2014; Orchard and Seward, 2002; Woods *et al.*, 2004) with running being the most common activity at time of injury (Brooks *et al.,* 2006; Kenneally-Dabrowski *et al.*, 2019b; Verrall *et al.,* 2005; Woods *et al.*, 2004). Hamstring function is a fundamental part of sprinting meaning a hamstring injury has significant negative consequences on an athlete's performance (Sun *et al.*, 2015). However, the precise mechanism of HSI and when during the running cycle the injury occurs is not known (Chumanov *et al.*, 2012; Orchard, 2012).

The re-injury rate for HSI has been reported to range between 16 to 31% (Croisier, 2004; Malliaropoulos *et al.*, 2011; Woods *et al.*, 2004) with the risk of re-injury described as being the greatest during the period of the first two weeks (Orchard and Seward, 2002) to the first month (Brooks *et al.*, 2006) of return to sport and reoccurrences often being more severe than the initial injury (Brooks *et al.*, 2006; Ekstrand *et al.,* 2011; Orchard and Seward, 2002). The high prevalence and re-injury risk of HSI within team sport has a significant financial implication on the clubs with the players losing game and training time (Dallinga *et al.,* 2012; Opar *et al.*, 2012; Wan *et al.*, 2017a). Ekstrand and colleagues (2011) report that HSI is the leading cause for prolonged absence (>28 days) from training and playing soccer and a recent study by Kenneally-Dabrowski *et al.* (2019b) observed that HSI resulted in a median of 26 days lost from training and competition in rugby union for each injury sustained and that an average of 207 days were lost per season as a consequence of the injury.

Rugby union causes some of the highest rates of injury in team sport (Kerin *et al.,* 2022; Williams *et al.*, 2013), thus identifying the need for strategies for both injury prevention and management (Coughlan *et al.*, 2011; Williams *et al.*, 2013). Rugby union players often play in both 15 a-side and rugby sevens events each of which have different requirements, including heightened running demands in a sevens game with players covering a 69% greater relative distance (Ross *et al.,* 2014), a larger running volume of approximately 45% and elevated high velocity running demands of approximately 135% (Higham *et al.*, 2012) compared to the 15 a-side game. Consequently, the elevated and overall intensity of the rugby sevens game presents a greater risk and incidence of injury (Fuller *et al.*, 2010).

The lower limb is the most commonly injured body part in 15 a-side and rugby sevens (Cruz-Ferreira *et al.,* 2017; Fuller *et al.*, 2011; Rizzi *et al.*, 2017; Williams *et al.*, 2013) with joint/ligament and muscle/tendon injuries accounting for over two thirds of injuries sustained (Cruz-Ferreira *et al.*, 2017). Hamstring strain injuries are the most common non-contact lower limb injury in rugby union (Brooks *et al.*, 2006) and a high prevalence of injury are reported in the sevens discipline (Rizi *et al.*, 2017). High-speed running is the most common mechanism for injury (Brooks *et al.,* 2006; Bourne *et al.*, 2015; Kenneally-Dabrowski *et al.*, 2019b) and may contribute to the HSIs which occur in rugby as high-speed running is an integral element of the sport as players need to accelerate and sprint to make position (Duthie *et al.,* 2006). High-speed running in rugby is different to straight-line running on a track due to carrying the ball and changing direction, however coaches continue to focus on their players' ability to run quickly in a straight line (Duthie *et al.,* 2003), with evidence demonstrating that elite 15's rugby union (Barr *et al.*, 2013) and sevens players (Higham *et al.*, 2013) reach their maximum velocity in the 30 – 40 m phase of running which is the period during which HSI have been reported to occur (Brooks *et al.*, 2006).

2.3 Mechanism of hamstring strain injury

The hamstring muscle group is comprised of the BFlh, BFsh, ST and SM, which are referred to as the lateral (BFlh and BFsh) and medial (ST and SM) hamstrings respectively (Thorburg *et al.*, 2020). Based on their function as hip extensors and knee flexors, the hamstring muscle group is often classified into monoarticular muscle (BFsh) or biarticular muscles (BFlh, ST and SM) (Onishi *et al.,* 2002). As a result of having a biarticular arrangement the hamstring muscles may be exposed to large length changes, particularly during running and kicking which involves concurrent hip flexion and knee extension as this limb position extends the bi-articular hamstrings (Askling *et al.*, 2007; Garrett, 1990; Peterson and Holmich, 2005) and this may place them at greater risk of injury.

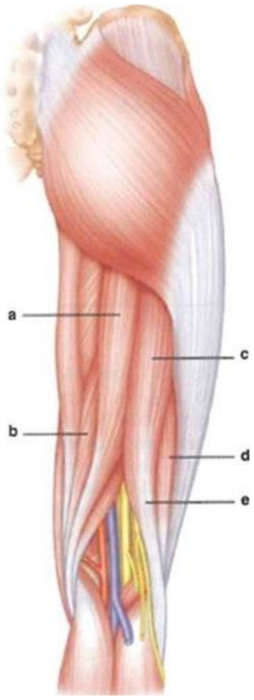

Figure 2.1 Illustration of the right thigh identifying the hamstring muscles. The medial hamstrings include a) ST and b) SM; and the lateral hamstrings include c and e) BFlh and d) BFsh (Kaeding and Borchers, 2014).

Muscle strain injuries are reported to occur during eccentric actions when muscles are lengthened beyond their optimal working length (Brockett *et al.*, 2004; Garrett, 1990; Yu *et al.*, 2017). Two types of HSI mechanism are described in the literature including a stretch-type injury which result from a combination of hip flexion and knee extension such as that which occurs during kicking and dance and largely involves the SM muscle (Askling *et al.*, 2000; 2007), and a sprint-type hamstring injury which happens during maximal or near maximal running speed (Askling *et al.*, 2000; Heiderscheit *et al.*, 2010) and mainly involves the BFlh (Askling *et al.*, 2007; Huygaerts *et al.,* 2021; Kenneally-Dabrowski *et al.,* 2019b). It is suggested that HSI most commonly occurs during high-speed running which involve high-intensity actions that stretch and place high mechanical loads on the muscle (Brooks *et al.*, 2006; Woods *et al.*, 2004), consequently, determining the mechanics of the hamstring muscle group during running is paramount to understanding the mechanism of injury.

Evidence shows that the BFlh is the most commonly injured muscle. Koulouris and Connell (2003) retrospectively analysed the imaging reports of 179 HSIs from 170 individuals from a range of sports including football (120 injuries), athletics (32 injuries), cricket (17 injuries) and water skiing (10 injuries) and reported that 80% of the injuries involved the BFlh. A recent study by Kenneally-Dabrowski and colleagues (2019b) described that 90% of HSI that occurred during running in rugby union affected the BFlh muscle. Other research concurs with these findings (Askling *et al.*, 2013; Bourne *et al.*, 2015; Koulouris *et al.*, 2007; Woods *et al.*, 2004). Furthermore, recurring HSI is also more common in the BF muscle (Bourne *et al.*, 2015; Brooks *et al.*, 2006; Hallen and Ekstrand, 2014; Koulouris *et al.*, 2007). There is no conclusive evidence to explain the predominance of HSI occurring in the BFlh muscle, however it may be linked to the fact that BFlh experiences the greatest musculotendon stretch and strain during the late swing phase of high-speed running (Chumanov *et al.*, 2011; Heiderscheit *et al.*, 2005; Higashihara *et al.*, 2016; Schache *et al.*, 2013; Thelen *et al.*, 2005a). Schuermans and colleagues (2014) suggest that insufficient neuromuscular, synergistic coordination and activity of BF and ST may contribute to the vulnerability of the BFlh injury. Furthermore, secondary injury to the ST muscle is commonly reported (Askling *et al.*, 2007; De Smet and Best, 2000). The higher rate of recurring HSI in the BFlh has been proposed to be associated with atrophy of the muscle (Silder *et al.*, 2008) and altered muscle architecture as a result of previous injury (Timmins *et al.*, 2014; 2017).

The morphology of the hamstring muscles is closely linked to their functional properties, which in turn influences the incidence of injury observed (Huygaerts *et al.,* 2021; Kumazaki *et al.*, 2012). The study of Kumazaki *et al.* (2012) reports that the BFlh and SM have shorter muscle fibres that shorten to a greater extent when contracted when compared to BFsh and

ST, and that the total changes in muscle length of the BFlh and SM during muscle contraction are two to three times larger than the BFsh and ST (Kumazaki *et al.*, 2012). Biceps femoris long head also exerts more force during a lengthening contraction, because it must lengthen over a larger distance (Dolman *et al.*, 2014; Thelen *et al.*, 2005a). Kumazaki and co-authors (2012) report that the knee flexion torque is significantly higher for all hamstrings when the knee is extended, which mirrors the findings of previous work (Onishi *et al.*, 2002). Consideration of knee flexion torque in conjunction with the morphological features and higher activity of the BFlh observed prompted the authors to conclude that the risk of muscle strain is greater in this muscle when compared to the other hamstrings (Kumazaki *et al.*, 2012).

Further reasons for BF injury proposed in the literature include the fact that BF has two heads and that the dual innervation may lead to asynchronous muscle stimulation and contraction which may decrease the hamstring's ability to generate sufficient tension to control the loads to which the muscle is exposed (Zuluaga *et al.*, 1995). A more recent study by Schuermans *et al.* (2014) suggests that the BFlh is injured more frequently due to the smaller fascicular length of the muscle when compared to the medial hamstrings. This limits its ability to produce force and control the torques in the hip and the knee at the end range of movement during the late swing phase of running, thus increasing the BFlh muscle's propensity for injury.

Research investigating hamstring mechanics during running have used different running speeds, with speeds of 7.0 m.s $^{-1}$ to 7.9 m.s $^{-1}$ being identified as high-speed or fast-paced running (Chumanov *et al.*, 2011; Schache *et al.*, 2014) and speeds of 8.0 m.s $^{-1}$ or more being identified as sprinting (Higashihara *et al.*, 2015a; 2016; Schache *et al.*, 2009; 2012; 2014; Thelen *et al.*, 2005b). Conversely, some studies imply that speeds of less than 8.0 m.s $^{-1}$ can be considered as sprinting (Schache *et al.*, 2010; Yu *et al.*, 2008) and others use the term high-speed running yet use sprinting when describing the methods and instructions to participants (Chumanov *et al.*, 2011). Collectively, it appears that the terms high-speed running and sprinting are used interchangeably and interpreted differently in the literature.

Consequently, it appears appropriate to suggest that sprinting may be better described as a person's relative maximal effort rather than by a set speed as maximum running speed will vary between individuals. For example, studies investigating sprinting most commonly include experienced sprinters who likely achieve higher speeds than athletes from high-speed running-based sports such as rugby and soccer. For the purpose of discussing the literature in this chapter the terms adopted by the respective studies will be retained and where studies have investigated different running speeds or percentages of maximal running speed, the specific details will be presented accordingly. However, the underlying working definition for this thesis will be that sprinting represents a person's maximal effort regardless of actual speed.

With sprinting being the most common mechanism of HSI, illustrating hamstring activation and function during sprinting, and activation during different exercises can serve to inform clinicians regarding exercises targeted at mitigating HSI risk. Therefore, the aim of this chapter is to:

1) Describe lower limb muscle activation during the different phases of sprinting.

2) Describe the kinematics and activation patterns of the hamstring muscles during sprinting.

3) Identify the phases of sprinting during which the hamstrings, and more commonly the BFlh, are most frequently injured.

4) Identify and discuss hamstring muscle activation during hamstring training exercises.

2.4 The running gait cycle

The stance phase accounts for approximately 30% of the running cycle and is the period that starts with the foot making initial contact with the ground and ends at toe off. This phase is divided into the early and late stance phase, with the mid-point being referred to as mid-stance which occurs at 15% of the cycle (Howard *et al.*, 2018). The swing phase accounts for approximately 70% of the running cycle. It begins at toe off and finishes with initial contact and is sub-divided into early swing, which is the period from toe-off to maximal knee flexion; middle swing which is the period from maximum knee flexion to maximum hip flexion and the late swing phase which is the period from maximum hip flexion to the next foot strike or ground contact (Higashihara *et al.*, 2010; 2015a; Howard *et al.*, 2018). The early and middle swing phase represent two thirds of the swing phase while the late swing phase signifies the latter third (Howard *et al.*, 2018).

2.4.1 Lower limb muscle activity during sprinting

Table 2.1 shows the methodological characteristics and key findings of studies investigating lower limb muscle activity during sprinting. These studies will be presented in the following section to portray the activity of the hamstrings, RF, GM and gastrocnemius which are the muscles commonly analysed during sprinting.

Table 2.1 Study characteristics investigating lower limb muscle activity during sprinting

Authors	Study population	Methods	Surface	Pattern of muscle activity
Higashihara *et al.* (2015a)	13 track & field athletes	Reflective markers & surface electrodes	Track	• BFlh most active during early stance, latter half of mid-swing and all of late swing • Medial hamstrings more active than BFlh during late stance & mid-swing
Jonhagen *et al.* (1996)	9 sprinters	Surface electrodes	Track	• Peak hamstrings & GM activity prior to & during foot strike • Peak RF activity mid-stance & swing. Gastrocnemius peak activity occurred prior to toe-off • Peak tibialis anterior start of swing & prior to foot contact
Mann *et al.* (1986)	15 runners	High-speed camera & surface electrodes	Gait laboratory runway	• Hamstrings active from mid swing to stance phase • Similar activity lateral & medial hamstrings • GM and quadriceps active during same period as hamstrings • Gastrocnemius active late-swing to toe-off
Mero & Komi (1987)	19 sprinters	High-speed camera, surface electrodes & force plates	Force platform	• Peak BF, GM, gastrocnemius & vastus lateralis during ipsilateral ground contact • Peak RF during contra-lateral contact • GM & vastus lateralis activity decreased in propulsion phase • BF & gastrocnemius primary role in propulsion during sprinting • Tibialis anterior activity starts after contact
Schache *et al.* (2013)	7 sprinters	Reflective markers & surface electrodes	Track	• Biarticular hamstrings active from foot strike to initial swing & late swing to contact

Mann and co-workers (1986) report that during sprinting, hamstring activity starts prior to the hip reaching maximal flexion, which aligns with the mid-swing phase (Higashihara *et al.*, 2015a) and reflects an eccentric hamstring contraction as the hip proceeds towards a position of maximal flexion (Mann *et al.*, 1986). Similar findings of medial and lateral hamstring activation from the mid-swing phase onwards have been observed (Higashihara *et al.*, 2010; Schache *et al.*, 2013). Hamstring activity continues through late swing as the muscles function to decelerate the leg and control knee extension while also generating hip extension. During the early stance phase hamstring activity continues as they contract concentrically to extend the hip. The GM muscle is also active during the early stance phase as it contracts concentrically to extend the hip while during the late swing phase it works eccentrically in conjunction with the hamstrings to decelerate the thigh (Mann *et al.*, 1986).

The quadriceps are the antagonists to the hamstring muscles and become active during the mid-swing phase (Mann *et al.*, 1986) which is denoted by the hip reaching maximal flexion (Higashihara *et al.*, 2015a). The activity of the quadriceps continues through the late swing phase where they contract concentrically to control extension of the knee joint through to foot contact and early stance during which eccentric contraction occurs to control the knee flexion which occurs during the support phase. Jonhagen and colleagues (1996) observed peak quadriceps activity during the stance phase and during the swing phase, with the latter demonstrating peak values which were double that observed during the stance phase of sprinting. Similar findings are reported by Mero and Komi (1987). Mann *et al.* (1986) report that the activity of the lateral and medial hamstring muscles is the same during sprinting which differs to the findings of Jonhagen and co-authors (1996) who report lower activity of the lateral hamstrings compared to the medial group. Further findings of non-uniform hamstring activity during sprinting have been reported (Higashihara *et al.*, 2015a).

In conjunction with the hamstrings, the gastrocnemius muscle also serves as a knee flexor in addition to being a plantar flexor of the ankle (Jonhagen *et al.*, 1996). During the late swing phase dorsiflexion of the ankle occurs and an eccentric contraction of gastrocnemius occurs to stabilise the ankle in preparation for foot contact, and peak activity occurs prior to ground contact (Jonhagen *et al.*, 1996). Gastrocnemius activity continues through the early stance phase to control the movement of the tibia over the foot and then contracts to plantar flex the ankle as toe off occurs. Mann and colleagues (1986) observed a small amount of ankle plantar flexion during the stance phase, which implies that the propulsion phase of the gait cycle is a result of hip flexion in the swing limb rather than the stance limb generating push off (Mann *et al.*, 1986). The latter contradicts the findings of other studies who observed high gastrocnemius activity during stance, including the toe-off phase and thus argue that the calf muscle has a key role in propulsion and push-off (Jonhagen *et al.*, 1996; Mero and Komi, 1987). Mann and co-workers (1986) did not normalise the sEMG data collected and therefore the findings were based on the temporal aspects of muscle activity. The latter requires consideration as normalisation of sEMG data is required to enable comparisons between different individuals, muscles and trials (Burden, 2010) and thus lack of such procedures limits direct comparison between research studies.

Higashihara *et al.* (2015a) investigated hamstring muscle activity during overground sprinting and observed a bi-phasic peak in muscle activation which was evident during late swing and early stance. This pattern of peak hamstring activity has been observed previously (Chumanov *et al.*, 2011; Yu *et al.*, 2008). Higashihara and colleagues (2015a) observed a non-uniform pattern of hamstring recruitment during sprinting. Biceps femoris long head generated higher activity during early stance compared with late stance, and when compared to the early part of the mid-swing phase, BFlh activity was greater during the latter half of mid-swing and the entirety of late swing. The findings demonstrated that BFlh activity increased prior to and after foot contact, findings which have been reported previously (Chumanov *et al.*, 2011; Jonhagen *et al.*, 1996) and reflect the hip extensor function of BFlh during late swing and early stance phase (Higashihara *et al.*, 2015a). The medial hamstrings demonstrated higher activity in the late stance phase when compared to BFlh, during which a degree of knee extension was observed, which would generate eccentric hamstring activation (Higashihara *et al.*, 2015a). Eccentric hamstring activity has previously been reported during the late stance phase of sprinting (Chumanov *et al.*, 2011; Yu *et al.*, 2008), and due to the morphology of the ST muscle resulting in selective recruitment during eccentric knee flexion activities (Ono *et al.*, 2010), the greater medial hamstring activity observed by Higashihara *et al.* (2015a) was inferred to be a result of ST activation. The medial hamstrings also generated greater activity during the first and latter half of mid swing compared to BFlh (Higashihara *et al.*, 2015a) While the medial hamstrings were assessed via one electrode, the findings were reported to be the result of the ST muscle working to control the hip flexion and knee extension that occurs concurrently during the mid-swing phase. The latter was reported to be a consequence of ST demonstrating the greatest muscle-tendon lengthening velocity during this phase of sprinting (Schache *et al.*, 2012; Thelen *et al.*, 2005b).

2.5 When does hamstring strain injury occur during sprinting?

There is a lack of consensus regarding when HSI occurs during the running gait cycle. Some research studies suggest that the late swing phase generates the greatest risk of injury (Chumanov *et al.*, 2012; Schache *et al.*, 2012; 2013; Yu *et al.*, 2008); while others state that the early stance phase is when HSI tends to occur (Mann and Sprague, 1980; Ono *et al.*, 2015; Orchard, 2012). Recent work however describes the swing-stance transition as the period during sprinting when the risk of HSI is at its greatest (Liu *et al.*, 2017).

2.5.1 The late swing or early stance phase? Kinematic studies

Table 2.2 shows the methodological characteristics of studies which have used kinematics to determine and identify when HSI occurs during the running gait cycle and will be discussed in the following section.

Table 2.2 Study characteristics investigating kinematic analysis to determine the phase of the running gait cycle when hamstring injury occurs

Authors	Study population	Methods	Surface	Measures used to confirm phase	Running cycle phase
Heiderscheit *et al.* (2005)	1 skier	Reflective markers & high-speed camera	Treadmill	Earliest indication of injury	Late swing
Higashihara *et al.* (2015b)	8 track & field athletes	Reflective markers & high-speed camera	Track	Muscle length	Stance
Mann and Sprague (1980)	15 sprinters	Reflective markers & high-speed camera	Track	Muscle moments	Early stance
Schache *et al.* (2009)	1 Australian rules footballer	Reflective markers, high -speed camera & force plates	Track	Earliest indication of injury	Late swing
Schache *et al.* (2010)	1 Australian rules footballer	Reflective markers, high-speed camera & force plates	Track	Hamstring length, force velocity, negative muscle work	Late swing
Sun *et al.* (2015)	8 sprinters	Reflective markers & high-speed camera	Track	Lower limb joint torques	Late swing & early stance
Thelen *et al.* (2005b)	14 athletes	Reflective markers & high-speed camera	Treadmill	Muscle length	Late swing

Using a three-dimensional motion analysis and musculoskeletal models, Thelen and co-workers (2005b) completed a study to estimate the lengths of the hamstring muscles of 14 athletes during treadmill sprinting at 80%, 85%, 90%, 95% and 100% of the athlete's maximum speed. Their findings revealed that the hamstring tendons lengthened from 45 to 90% of the gait cycle and that the hamstring group was experiencing a lengthening contraction during the late swing phase, which concurs with other work (Chumanov *et al.*, 2011; Mann *et al.*, 1986; Yu *et al.*, 2008). The peak musculotendon length occurred during late swing prior to foot contact (BF 90% gait cycle, ST and SM 92% gait cycle), with BF experiencing the greatest overall stretch (10% vs. 8% for both ST and SM longer than upright posture) and the corresponding hip and knee joint flexion angles during this time was approximately 55-65° and 30-45° degrees respectively (Thelen et *al.*, 2005b). The finding of peak ST musculotendon length occurring later than BF mirrors the findings of Schache *et al.* (2012), however the latter study analysed BFlh while Thelen and colleagues (2005b) stated BF only.

Running speed did not significantly influence the lengths of the hamstring muscle-tendon unit (MTU), however, the peak lengths measured occurred significantly later in the gait cycle at the maximal running speed (mean maximal speed for males and females was 9.4 m.s $^{-1}$ and 8.1 m.s $^{-1}$ respectively). While hip flexion did not differ significantly with speed, knee flexion was significantly greater during the late swing phase at the maximum running speed compared to the slowest speed. Thelen *et al.* (2005b) state that when considering injury risk, thought needs to be given to muscle fibre length and pennation angles in conjunction with muscle-tendon length and strain. The ST muscle has a fusiform shape with longitudinal muscle fibres while the BFlh and SM have a hemi-pennate arrangement with a shorter fibre length per total muscle length which results in an elevated risk of muscle strain injury (Kumazaki *et al.*, 2012).

A point of consideration for the study completed by Thelen *et al.* (2005b) is the use of treadmill sprinting. Differences between treadmill and overground running have been reported, including a larger knee flexion angle at toe off (Frishberg *et al.*, 1983), smaller peak hip flexion angles during foot strike (Sinclair *et al.*, 2013) and a lower magnitude of muscle activation during the stance phase (Wang *et al.*, 2014) of treadmill running. Conversely, some report that treadmill and overground running are similar with comparable findings of hamstring length, load and activation being reported during treadmill and overground running (Chumanov *et al.*, 2011; Heiderscheit *et al.*, 2005; Schache *et al.*, 2011; 2013; Wank *et al.*, 1998). The lack of conclusive findings require acknowledgement when comparing the findings of studies that have used different methods of investigating sprinting. A further consideration to note regarding the study completed by Thelen and colleagues (2005b) is the use of a musculoskeletal model that was unable to account for any variation regarding the origin and insertion of the muscles of the participants included in the study, which would change the size of the muscle tendon lengths (Thelen *et al.*, 2005b).

Heiderscheit and colleagues (2005) utilised a single case study approach in an attempt to ascertain when HSI occurs during the gait cycle. The participant was required to run on a treadmill at different speeds and inclinations and during data collection, they sustained a right HSI. By using a three-dimensional musculoskeletal model, the authors were able to calculate joint angles and hamstring muscle-tendon lengths to assess the approximate time during which the injury occurred. As a result of their assessment the late swing phase was reported as the time frame during which the injury happened. The study showed that the BFlh MTU was undergoing an active lengthening action during late swing, contributing to the potential and susceptibility for injury. At the time of injury all three hamstring muscles were at their peak MTU length, with BF reaching peak length earlier than ST and SM. Additionally, a disparity was observed in the degree of peak stretch between the medial and lateral hamstrings (Heiderscheit *et al.*, 2005) with BFlh experiencing a stretch that was estimated to be 12% greater relative to upright, which was linked to the observation of increased hip and knee flexion angles corresponding to peak BFlh length at the point of a HSI when compared to an injury free limb (69° and 58° vs. 65° and 50° respectively).

Similar findings of greater peak BF stretch compared to the medial hamstrings has previously been observed and inferred to be a consequence of inter-muscle differences in muscle morphology and knee flexion moment arms (Thelen *et al.*, 2005b; 2006). Biceps femoris long head has a smaller knee flexion moment than the medial hamstring muscles such that the knee flexion which occurs during late swing results in the BFlh experiencing a greater degree of stretch due to the simultaneous extension action happening at the hip (Thelen *et al.*, 2006). It has previously been acknowledged that the amount of muscle strain experienced is a significant contributing factor in the mechanism of injury during lengthening muscle actions

(Lieber and Friden, 1993; Schache *et al.*, 2012). In the absence of obtaining a baseline measure of muscle length at rest, it was not possible to calculate the mechanical strain, however it was suggested that the MTU stretch was an indirect indication of strain, and that BFlh experienced a large mechanical strain during the late swing phase of the injured limb (Heiderscheit *et al.*, 2005), thus making it vulnerable to injury.

Hamstring strain injuries are most commonly reported in sports which include high-speed running such as rugby, soccer and track and field (Brooks *et al.*, 2006; Croisier, 2004; Ekstrand *et al.*, 2011; Kenneally-Dabrowski *et al.*, 2019b; Orchard and Seward, 2002). Consequently, the generalisability of the results of Higashihara and colleagues (2005) could be questioned as the subject utilised for the study was a skier. Furthermore, one may query why a range of different running inclines were used as part of the methodology as the aforementioned sports are performed on level surfaces in the absence of an incline. No detail was provided regarding the number of running trials, duration of running for each trial or rest period between the trials which questions whether fatigue may have had an influence on the findings as this has been reported as a risk factor for HSI (Pinniger *et al.*, 2000; Small *et al.*, 2010). Finally, as acknowledged earlier in this chapter, differing findings and opinion about treadmill versus overground running require acknowledgement.

Schache *et al.* (2009) further provide a case study-based finding of HSI occurring during the late swing phase of sprinting. Both kinematic and ground reaction force data were collected during overground sprinting in an attempt to identify potential risk factors to HSI. Using an elite Australian rules male football player with a history of recurrent right HSI, data was obtained to establish if there were any asymmetries in running gait. The player experienced a right HSI during the final (10^{th}) running trial and the data revealed that compared to the non-injured limb, the injured leg demonstrated a greater hamstring muscle-tendon length which happened earlier in the late swing phase. Furthermore, the hip extension and knee flexion moments were lower in the injury trial limb compared to the non-injured trial, a finding which differs to that of Heiderscheit and colleagues (2005) and may be due to the differing HSI history of the participants involved as altered muscle activity and kinematics are evident after HSI (Daly *et al.*, 2016). Based on the findings of an initial kinematic deviation in relation to the trunk and pelvis occurring in the stance phase during the injury trial, it was proposed that due to the electromechanical delay, the stimulus for the injury would have taken place during the swing phase (Schache *et al.*, 2009). Similar findings with regards to the detection of kinematic deviation and consideration of neuromuscular latency and electromechanical delay in determining the timing of HSI during high-speed running have been reported previously (Heiderscheit *et al.*, 2005). However, predicting neuromuscular latency is difficult (Schache *et al.*, 2009) and thus while the observations of the of HSI reported by the aforementioned authors identifies the late swing phase as the period where injury occurred, further research is needed to substantiate the findings.

Orchard (2012) argues that methods of determining the likely point of HSI such as those used by Heiderscheit *et al.* (2005) and Schache and colleagues (2009) is based largely on speculation and presents indirect evidence, and that the time frames presented by Heiderscheit and colleagues (2005) in which they propose injury occurred included early stance also. Orchard (2012) argues that the stance phase joint moments are considerably higher than those in the swing phase, and therefore the hamstrings are subject to large loads which creates a greater risk for injury. The latter opinion is corroborated by earlier research by Mann and Sprague (1980) who suggest HSI occurs during the early stance phase because the hip extension and knee flexion torques are at their greatest during foot contact as a consequence of the ground reaction force (Mann and Sprague, 1980; Orchard, 2012).

While there are methodological points to be considered, collectively, research utilising kinematic procedures identify that the hamstrings reach their longest length and peak MTU stretch (Chumanov *et al.*, 2007; Thelen *et al.*, 2005a; 2005b; Wan *et al.*, 2017a) and peak force (Schache *et al.*, 2010; 2012) in the late swing phase. The latter suggets that this phase of high-speed running presents great potential for HSI and supports research findings which adopted sEMG in conjunction with kinematic measures.

2.5.2 The potential for hamstring strain injury during the late swing and early stance phases

While literature argues that the hamstrings are at risk of injury during either the late swing and early stance of sprinting, Sun and co-workers (2015) analysed overground sprinting and deduced that the hamstring muscles are at risk of injury during both the early stance and late swing phases. In addition to these latter findings, rather than viewing late swing and early stance as two phases, a recent study by Liu and colleagues (2017) proposes the consideration of a swing-stance transition. The authors argue that during the late swing phase, the hamstring muscle torques counter the passive effect caused by the inertia of the leg, while during the stance phase the active hamstring torque counter the ground reaction force experienced. Consequently, the period of time from late swing through to early stance presents a high risk of HSI, hence the proposal of the swing-stance transition phase (Liu *et al.*, 2017). The latter in conjunction with evidence of hamstring activity being at its highest during the late swing and early stance phases of sprinting (Hegyi *et al.*, 2019b; Higashihara *et al.*, 2015b; Yu *et al.*, 2008) further supports the evidence and opinion presented regarding one continuous window of HSI risk (Liu *et al.*, 2017; Sun *et al.*, 2015) rather than two separate phases of the cycle.

2.5.3 The late swing or early stance phase? Kinematic and surface electromyography studies

The use of kinematic analysis alone, only examines hamstring lengthening and not active muscle lengthening. In conjunction with kinematic procedures, some research studies have adopted sEMG to analyse the hamstring muscles during sprinting as a means of identifying the phase of sprinting during which HSI occurs. Table 2.3 shows the methodological characteristics of these studies and the following section will discuss the key findings pertaining to this research.

Table 2.3 Study characteristics investigating kinematic and electromyographic analyses to determine the phase of the sprinting cycle when hamstring injury occurs

Authors	Study population	Methods	Surface	Measures used to confirm phase	Running cycle phase
Chumanov *et al.* (2011)	12 runners	Reflective markers, high-speed cameras & surface electrodes	Treadmill	Eccentric contraction	Late swing
Higashihara *et al.* (2016)	13 track & field athletes	Reflective markers, high-speed cameras & surface electrodes	Track	Muscle activity and musculotendon length	Late swing
Ono *et al.* (2015)	12 athletes (Running based sports)	Reflective markers, high-speed cameras, surface electrodes & force plates	Track	Tensile force length x muscle activity	Early stance
Schache *et al.* (2012)	7 sprinters	Reflective markers, high-speed cameras, surface electrodes & force plates	Track	Peak force, negative work& hamstring lengthening	Late swing
Yu *et al.* (2008)	20 runners (or soccer or lacrosse)	Reflective markers, high-speed cameras & surface electrodes	Track	Eccentric contraction	Late swing & late stance

In an attempt to determine when the hamstring muscles are most prone to injury Chumanov *et al.* (2011) analysed the kinematics of the hamstrings of 12 subjects during treadmill running at five different incremental speeds of the subject's maximum running speed. Hamstring muscle activation (BF, ST and SM) was low during the early and mid-part of the swing phase, while two large peaks in activity were evident during the late swing and early stance phase, which mirrors previous work (Higashihara *et al.*, 2015a; Schache *et al.*, 2013). The hamstrings lengthened and performed negative work in the swing phase only, with a shortening of the hamstring MTU being observed during the stance phase. Previous studies have also reported a lengthening action of the BFlh, ST and SM muscles during late swing (Chumanov *et al.*, 2007; Schache *et al.*, 2012; Thelen *et al.*, 2005b) and shortening during the stance phase (Schache *et al.*, 2012).

Chumanov and colleagues (2011) observed increases in the amount of negative and positive work as speed increased, however the total negative hamstring work increased at a quicker rate as speed increased. Increases in the amount of negative hamstring work as a consequence of increasing running speed have previously been observed (Chumanov *et al.*, 2007). At the fastest running speed Chumanov and colleagues (2011) report that the ST peak forces did not demonstrate any significant differences across the running cycle. However, the amount of load experienced by BF increased with speed during the swing phase but not stance, and the peak BF stretch and negative work occurred exclusively during the swing phase (Chumanov *et al.*, 2011). The BF also demonstrated the largest peak musculotendon stretch when compared to ST and SM; a finding which has been previously reported (Chumanov *et al.*, 2007; Schache *et al.*, 2009; Thelen *et al.*, 2005b). Of note here is the fact that Schache and colleagues (2009) and Thelen et al. (2005b) specified BFlh in their research, while Chumanov *et al.* (2011) merely state BF and did not specify either the BFlh or BFsh portions of the lateral hamstring muscle.

Based on the findings of negative hamstring work occurring during the swing phase, and that the load experienced increased with speed in the swing phase only, the authors concluded that this is the phase in which the hamstrings are at most risk of injury and that the risk is greater at higher running speeds (Chumanov *et al.*, 2011). While Chumanov and colleagues (2011) made reference to muscle activation the main focus of discussion was directed more towards the stretch and load on the hamstrings. However, the aforementioned findings, in conjunction with the observed peak in BF activity in the late swing phase, may contribute to the propensity for BFlh injury in this phase of running. Similar findings of increased knee flexor load during late swing with faster overground running speeds are reported by Schache and colleagues (2011), however the latter study did not identify specific knee flexor muscles, therefore direct comparison to the results of Chumanov and colleagues (2011) is somewhat limited. The influence of running speed on hamstring activity will be discussed in more detail later in this chapter.

Lengthening of the hamstring muscle group during the late swing phase, and a shortening prior to touch down during overground high-speed running has further been reported by Schache and colleagues (2012). The late swing phase was identified as generating peak hamstring strain and force, and the amount of negative work performed was at its highest during this phase. Furthermore, BFlh experienced the greatest peak strain which occurred prior to the ST and SM muscles. Collectively, the time during which the stretch-shortening cycle occurred resembled the period of hamstring activation recorded by Schache *et al.* (2012) which concurs with other studies (Higashihara *et al.*, 2010; Jonhagen *et al.*, 1996; Yu *et al.*, 2008), and the large loads estimated during the late swing phase mirror studies that have reported peak lateral and medial hamstring activity during this phase (Chumanov *et al.*, 2011; Higashihara *et al.*, 2010; Yu *et al.*, 2008).

Findings presented by Higashihara and co-workers (2016) illustrate that during overground sprinting, hamstring muscle length is at its maximum during the late swing phase. When compared to the ST muscle, peak musculotendon length of BFlh occurred significantly later in the late swing phase; a finding that differs to Schache and colleagues (2012) and may be a consequence of differences in in the musculoskeletal models used which may influence the estimations of musculotendon length. Higashihara *et al.* (2016) further observed that BFlh activation was observed in the latter half of the swing phase, a finding that reached statistical significance compared to the ST muscle which demonstrated peak length and activation earlier in the swing phase. Furthermore, peak BFlh length and activation occurred simultaneously, while for the ST a significant difference was seen between peak length and activation. The findings presented by Higashihara and co-workers (2016) depict that the late swing phase subjects the BFlh muscle to high tensile force and thus generates a greater risk of injury when compared to ST, thus providing insight into the higher incidence of HSI in the

BFlh muscle (Askling *et al.*, 2007; Brooks *et al.*, 2006; De Smet and Best, 2000). Similar to Schache and colleagues (2012), Higashihara *et al.* (2016) adopted a single running trial method. While several running trials may have been viewed as beneficial to record the data which represented a successful trial, participants completed multiple attempts and thus a single trial was chosen as the preferred method to limit the effect of fatigue.

Yu and colleagues (2008) investigated hamstring muscle activity and kinematics during overground sprinting and observed eccentric hamstring contraction during the late swing phase; a finding that mirrors other studies (Chumanov *et al.*, 2011; Schache *et al.*, 2012). In addition to the late swing phase and in contrast to other studies, eccentric contraction was also reported during the late stance phase prompting the authors to conclude that there is potential for HSI during the late stance phase. The disparity in findings may be influenced by the fact that Yu and co-workers (2008) focused on the acceleration phase of overground high-speed running. The degree of anterior pelvic tilt and hip flexion increases during acceleration as the trunk is in a forward lean position when compared to running in an upright position, and thus influences hamstring muscle stretch and length (Higashihara *et al.*, 2015b) and requires consideration when interpreting research findings.

Conversely to the aforementioned research, Ono and colleagues (2015) propose that BFlh injury occurs during the early stance phase. Using changes in muscle-tendon length and normalised muscle activity, the authors estimated tensile force during overground sprinting and reported that the muscle-tendon length of the BFlh muscle peaked later in the gait cycle compared to the medial hamstrings and the peak tensile force was observed during the late swing phase. However, these peak values were similar to the ST muscle and thus the authors concluded that the timing of muscle activation determines the hamstring injury risk phase, with peak BFlh activity occurring during early stance which corresponded to the time of peak ground reaction force. The latter was proposed to generate a greater risk of injury in the BFlh muscle during early stance and may contribute to the increased propensity for injury in this muscle when compared to its medial counterparts (Ono *et al.*, 2015).

Collectively, studies utilising sEMG and kinematic procedures demonstrate that HSI is more likely to occur during the late swing phase of sprinting. Peak hamstring activity, amount of negative work completed and musculotendon length and strain are key parameters which influence the vulnerability of the hamstrings. The latter appear to contribute to the increased propensity for the injury in the BFlh muscle as it works eccentrically (Yu *et al.*, 2008), experiences peak activation and length (Higashihara *et al.*, 2016) and encounters greater strain compared to the medial hamstring group (Schache *et al.,* 2012) during the late swing phase of sprinting. Furthermore, the load experienced by BFlh increases with speed during the swing phase but not during stance (Chumanov *et al.*, 2011).

2.6 Hamstring injury risk and prevention

An array of literature argues that the hamstrings are most vulnerable to injury during the late swing phase of sprinting (Chumanov *et al.*, 2011; Heiderscheit *et al.*, 2005; 2015; Schache *et al.*, 2009; 2012) while there is some evidence which portrays the early stance as the injury risk period (Mann and Sprague, 1980; Ono *et al.*, 2015) other research suggests that a transition between the late-swing and early stance phase is the period where HSI risk is elevated (Liu *et al.*, 2017; Sun *et al.*, 2015). The lengthening of the hamstring MTU that occurs during late swing is reported to represent an eccentric contraction (Chumanov *et al.*, 2011; Higashihara *et al.*, 2015a; Schache *et al.*, 2012) and this has been inferred as being representative of active eccentric muscle contraction which places the hamstrings at risk of injury and thus exercises with an eccentric bias have been chosen for hamstring training (Van Hooren and Bosch, 2017a). However, this opinion has recently been challenged with suggestions being proposed of muscle fascicles acting isometrically while a lengthening of the tendon occurs during late swing (Van Hooren and Bosch, 2017a).

Van Hooren and Bosch (2017a) propose that the series elastic element, described as including the tendon, aponeurosis and connective tissues, may stretch and recoil during the swing phase of running while the muscle fascicle remains in an isometric condition (Van Hooren and Bosch, 2017a). Further, the authors argue that as muscle activity increases in response to increased movement intensity, that such behaviour of the contractile versus the series elastic element of the MTU would be expected during maximal velocity sprinting. This proposal of the muscle fascicles remaining in an isometric position while the tendinous element assists lengthening is established on findings from animal studies (Gillis *et al.*, 2005) and other lower limb muscles (Bohm *et al.*, 2018) rather than the hamstrings and thus further research is required to substantiate this. Knowledge and understanding of hamstring mechanics during sprinting is necessary to inform and develop injury prevention and training programmes. In particular, the divergent hamstring muscle responses which have been observed during sprinting (Higashihara *et al.*, 2010; 2015a), in conjunction with new opinions challenging the concept of eccentric muscle action during the late swing phase (Van Hooren and Bosch, 2017a), require acknowledgment when considering HSI prevention and the selection of hamstring training exercises which aim to mitigate HSI risk.

Hamstring strain injury is multi-factorial in nature and a number of modifiable risk factors for HSI have been identified including a shorter BFlh fascicle length (Timmins *et al.*, 2014; 2016a; 2017), reduced muscle strength (Lee *et al.*, 2018; Timmins *et al.*, 2016a), muscle fatigue (Brooks *et al.*, 2006; Small *et al.*, 2009), decreased hamstring strength-endurance (Freckleton *et al.*, 2014; Schuermans *et al.*, 2016) and neuromuscular co-ordination (Sherry and Best, 2004; Schuermans *et al.*, 2014). The next section of this chapter will discuss studies which have investigated risk factors for HSI as a means of improving injury prevention practices.

2.6.1 Neuromuscular co-ordination

Numerous studies report that HSI occur during late swing phase of sprinting (Chumanov *et al.*, 2007; Chumanov *et al.*, 2011; Chumanov *et al.*, 2012; Heiderscheit *et al.*, 2005; Schache *et al.*, 2009; Schache *et al.*, 2010). Therefore, knowledge of the influence of proximal lower limb musculature provides an insight to the importance of neuromuscular control as coordination of the hamstrings with synergists and stabilisers of the hip and knee joints is necessary for sprinting (Schuermans *et al.*, 2017a; 2017c). Consequently, these muscles need to be considered to identify their possible contribution to HSI and mitigation of injury risk.

Neuromuscular coordination and the ability to control the lumbopelvic region during higher-speed skilled movements may also have a role to play in HSI prevention (Sherry and Best, 2004; Thelen *et al.*, 2006). Comparison of a traditional hamstring rehabilitation approach of strengthening and stretching exercises with a programme including agility and trunk stabilisation by Sherry and Best (2004) revealed a significant difference in the rate of hamstring re-injury between both groups. During the first two weeks after returning to sport, six participants in the group which were prescribed strengthening and stretching exercises experienced a re-injury of their hamstrings, while no re-injuries were observed in the experimental group. Sherry and Best (2004) acknowledged that they were unable to present direct evidence to show that the reduced injuries were a result of enhanced trunk stabilisation or neuromuscular control however, a proposed theory for this encouraging finding was that enhanced control of the lumbopelvic area enables the hamstring group to operate at safe lengths and loads. The study investigated athletes from a range of sports which makes the findings applicable to a wide population and while the focus was rehabilitation, considering the significance of lumbopelvic strength and neuromuscular control from an injury prevention perspective is also noteworthy.

Numerous studies have investigated hamstring muscle activation in conjunction with neuromuscular coordination (Opar *et al.*, 2013; Schuermans *et al.*, 2014; 2016; 2017a). Opar *et al.* (2013) report that athletes who have completed their hamstring rehabilitation and have returned to sport continue to demonstrate suppressed BFlh activity, therefore suggesting that neural function and the role of neuromuscular inhibition in re-injury should be considered during the recovery process. Schuermans *et al.* (2014) state that susceptibility to HSI and re-injury is influenced by neuromuscular alterations between the BF and ST muscles. The findings of this study involving 54 amateur soccer players (27 with and 27 without a history of HSI) demonstrated that following a fatiguing prone hamstring curl exercise, the metabolic activity of the ST muscle measured via functional magnetic resonance imaging (fMRI), in previously injured participants was lower and somewhat compensated for by the activity of the BFlh and BFsh.

A follow-up prospective study by Schuermans and co-workers (2016) involving 44 male amateur soccer players further states that intramuscular interaction of the hamstrings influences injury risk. The findings determined that a significantly elevated risk of sustaining a first time HSI occurred if the activation of BF was greater than 10% of its metabolic resting state or if the ST muscle was not contributing enough to the exercise, thus implying that load sharing and an imbalance in muscular contribution influences HSI. Additionally, the authors concluded that the risk of re-injury was related to reduced hamstring muscle endurance. Collectively, these findings suggest that hamstring muscle fatigue and injury risk are influenced by intramuscular coordination and that programmes targeted at addressing injury risk need to consider not only the most commonly injured BFlh, but also the ST muscle.

In conjunction with intramuscular coordination, HSI risk has also been related to the intermuscular coordination and the relative contribution and influence of lumbopelvic muscles. Schuermans *et al.* (2017a) describe how activity of the proximal core muscles, described as including GM, oblique muscles and thoracic and lumbar erector spinae, during the swing phase of maximal acceleration toward full sprinting provides a protective mechanism against HSI. A group of 60 amateur soccer players were monitored for a period of 18 months after baseline testing and those who experienced a subsequent HSI (n = 15) displayed reduced levels of GM activity during late swing and decreased trunk muscle activity during the early swing phase when compared to players who did not sustain a HSI. Gluteus maximus serves to decelerate the thigh in the late swing phase and to extend the hip during stance (Mann *et al.*, 1986; Schache *et al.*, 2010) and it is reported to serve as a trunk stabiliser during running (Liberman *et al.*, 2006) with weakness in this muscle being proposed as a contributing factor to HSI (Sugiara *et al.*, 2008). The findings established a direct relationship between proximal muscle functioning during the swing phase of sprinting prompting the authors to conclude that neuromuscular control of the core affords sufficient stability during running and thus presents as a means of injury prevention (Schuermans *et al.*, 2017a).

Schuermans and co-workers (2017a) used maximal voluntary isometric contractions (MVIC) per muscle for data normalisation purposes which is very different to the dynamic task of sprinting, and thus requires some consideration when interpreting the findings as some argue that MVIC do not elicit truly maximal contractions (Burden, 2010). However, similar findings of BFlh activity during the late swing phase of sprinting have been reported in studies where differing methods of data normalisation were used, namely a maximal voluntary contraction (Higashihara *et al.*, 2010a) and sprinting (Higashihara *et al.*, 2016). Therefore, while the method of normalisation influences between muscle comparisons, there appears to be no consensus as to which is the most suitable with some suggesting maximal voluntary isometric contractions while others advocate the use of dynamic methods (Albertus-Kajee *et al.*, 2011; Burden, 2010).

A prospective study by Schuermans and colleagues (2017b) using amateur soccer players reported altered lumbopelvic and lower limb kinematics during acceleration to maximal speed running in four players who suffered HSI in the follow-up period. Injured players demonstrated significantly increased anterior pelvic tilt during the early swing phase and side flexion of the trunk during late swing of high-speed running, such findings were not observed in the sample of 25 uninjured players (Schuermans *et al.*, 2017b). With the pelvis in a position of anterior tilt, the hamstrings are stretched thus changing the length-tension relationship of the muscle which decreases its ability to generate force at longer lengths (Buckthorpe *et al.*, 2018), lengths which are typically experienced during the late swing of sprinting and thus may influence HSI risk. While Schuermans and colleagues (2017b) provide evidence illustrating that lumbopelvic motion may play a role in HSI risk, it is not clear whether the altered kinematics were a consequence of reduced strength or running coordination and technique and thus further investigation is required.

Kenneally-Dabrowski *et al.* (2019c) concur with the findings of Schuermans and colleagues (2017b) regarding trunk position as three out of 10 rugby players who subsequently experienced a hamstring injury demonstrated increased lateral thoracic flexion to the ipsilateral side during the late swing phase of overground sprinting. No difference in anterior pelvic tilt was found which differs to Schuermans and colleagues (2017b). In addition to the altered trunk kinematics, Kenneally-Dabrowski *et al.* (2019c) observed that injured players absorbed larger power at the knee which the authors implied illustrates the work done to decelerate the limb in preparation for foot strike as previously reported (Chumanov *et al.*, 2007; Thelen *et al.*, 2005b). Furthermore, the injured players generated a larger hip extension moment during late swing, a finding previously reported in HSI (Heiderscheit *et al.*, 2005) which would result in greater demands on the hamstring muscles while also working at the knee (Kenneally-Dabrowski *et al.*, 2019c) thus implying the importance of trunk and lumbo-pelvic control. The latter did not include the stance phase in their analysis yet this phase of sprinting has been reported to influence hamstring injury vulnerability as the muscles generate high activation and force (Mann and Sprague, 1980; Sun *et al.*, 2015; Yu *et al.*, 2008).

Previous observations of altered muscle activation and kinematics observed by Chumanov and colleagues (2007) support the findings reported by the aforementioned studies. Via the use of biomechanical modelling, Chumanov *et al.* (2007) deduced that altered lumbopelvic muscle activity and coordination influences the degree of hamstring stretch experienced during the late swing phase of sprinting. The authors concluded that inadequate activity of the hip extensors and over activity in the hip flexors influence the strain experienced by BFlh and thus injury risk, and that more GM force may serve to lessen the load experienced by BFlh (Chumanov *et al.*, 2007). Furthermore, during sprinting the hip extension torques can reach values that are twice as much as those of knee flexion, therefore any decrease in gluteus maximus activity or strength would result in the hamstrings experiencing greater demands (Higashihara *et al.*, 2018).

A recent study by Mendiguchia and colleagues (2022) reports that an intervention including exercises to address lumbopelvic control in addition to a running programme provided beneficial effects on the degree of anterior pelvic tilt. These findings support the earlier work of Chumanov *et al.* (2007) and Schuermans *et al.* (2017a) which illustrates the potential effect that the gluteal musculature has on the degree of BF strain during high-speed running. Such findings illustrate the role that lumbopelvic muscle coordination has in safeguarding the hamstring muscles during high-speed running. Collectively, the findings from the aforementioned studies provide insight into the relationship between sprinting mechanics and injury, and in particular demonstrate that coordination and interplay of the hamstrings and lumbopelvic muscles contributes to the vulnerability of the hamstrings to strain injury. However, more prospective studies are needed to further clarify this relationship.

2.6.2 Hamstring muscle strength – the effect of eccentric hamstring training exercises

It has been suggested that athletes are more at risk of muscle strain injury if they generate peak torque at shorter muscle lengths (Brockett *et al.*, 2001; Brockett *et al.*, 2004) and if weakness is evident at longer muscle lengths (Opar *et al.*, 2014; Schmitt *et al.*, 2012). Evidence also shows that athletes are at greater risk of recurrent HSI if there is a lack of eccentric hamstring muscle endurance (Freckleton *et al.*, 2014; Schuermans *et al.*, 2016). Eccentric strength training produces greater shifts in the length tension relationship of a muscle (Brughelli and Cronin, 2007) and changes the optimum length at which a muscle generates torque (Brockett *et al.*, 2001). This implies that eccentric exercise should be considered for hamstring muscle training programmes to increase outer range muscle strength in an attempt to decrease the rate of muscle strain injury (Brockett *et al.*, 2001; Schmitt *et al.*, 2012).

The mechanism of HSI during sprinting includes an active lengthening of the MTU in the late swing phase Chumanov *et al.*, 2011; Higashihara *et al.*, 2015a; Schache *et al.*, 2009). Consequently, in an attempt to mitigate injury risk, hamstring training including eccentric strength training has been proposed as a means of mirroring injury mechanics and the concurrent movements at the hip and knee during sprinting (Schache *et al.*, 2012) and to activate and load the muscles at a longer lengths. Evidence shows that between six to 12 weeks of eccentric training and increasing eccentric hamstring muscle strength reduces HSI incidence by up to 75%, with findings being presented from a variety of sports, including rugby (Brooks *et al.*, 2006), soccer (Peterson *et al.*, 2011; van der Horst *et al.*, 2015) and baseball (Seagrave *et al.*, 2014).

The Nordic Hamstring Exercise (NHE) is a commonly used exercise for hamstring training as it maximises eccentric muscle loading (MjØlsnes *et al.*, 2004) and has been the focus of hamstring related research with specific focus on the exercise generating increases in muscle strength (Iga *et al.*, 2012; MjØlsnes *et al.*, 2004;), increases in fascicle length (Bourne *et al.*, 2017a; Ripley *et al.,* 2023; Timmins *et al.*, 2016b) and reducing HSI incidence (Peterson *et al.*, 2011; Seagrave *et al.*, 2014; van der Horst *et al.*, 2015). Peterson *et al.* (2011) utilised a 10-week protocol and demonstrated that in a cohort of 942 professional soccer players, the NHE decreased the rate of initial HSI by 70% and that the protocol was also effective at reducing recurrent HSI with the study observing a reduction rate of 86%. van der Horst and colleagues (2015) concur with the findings of Petersen *et al.* (2011) and showed a significant reduction in HSI risk in a sample of 579 amateur soccer players with those who completed the training programme experiencing 69% fewer HSIs. Similar findings of the beneficial effects of the NHE on HSI incidence have also been reported in professional baseball (Seagrave *et al.*, 2014) and professional rugby union (Brooks *et al.*, 2006).

While studies have utilised trained, professional participants (Peterson *et al.*, 2011; Seagrave *et al.*, 2014) no reference was made to whether specific hamstring training exercises were already part of their regime, thus it is difficult to deduce the influence and benefit of eccentric biased exercises when strength training is already included. However, in contrast to the latter studies, Brooks and colleagues (2006) investigated the effect of eccentric exercise in addition to strength training which included concentric and eccentric exercises in professional rugby union players. The findings confirmed a significant decrease in HSI incidence in the group that completed the NHE as part of their training programme. While the latter was a significant finding, the NHE was not compared to another exercise of similar intensity and thus confirming whether the finding was due to the muscle contraction type or the intensity of the exercise is limited (Van Hooren and Bosch, 2017b).

MjØlsnes and colleagues (2004) examined the effect of a 10-week eccentric NHE intervention compared to a 10-week concentric hamstring curl intervention on hamstring strength. No strength improvements were observed in the hamstring curl group, however improved eccentric and isometric strength was observed in the NHE intervention group. It was recognised that at the end of the training protocol, some of the players had improved their strength to such an extent that they were able to stop the downward motion of the NHE completely before touching the ground. The authors argued that this resembles the reported HSI mechanism as the muscles were acting eccentrically in the presence of high forces and the knee was approaching full extension (MjØlsnes et al., 2004). Hamstring strain injuries are reported to occur during high velocity muscle actions (Stanton and Purdham, 1989), and poor eccentric hamstring strength at high velocities is one of the reported causes of hamstring re-injury (Jonhagen *et al.*, 1994). One limiting factor observed in the study by MjØlsnes and colleagues (2004) was that the participants were tested at $60°s^{-1}$. Therefore, it was not possible to conclude if the effects of the NHE are velocity dependent.

To determine whether strength gains from the NHE are velocity dependant, Iga and colleagues (2012) conducted a four-week NHE intervention and tested eccentric strength at 60°, 120° and $240°s^{-1}$ pre and post the intervention. Their findings demonstrated improvements in eccentric hamstring muscle strength across all velocities, with significant improvements in peak torque of up to 21% being observed in all test conditions. These findings indicate that the benefits of the slow angular velocity NHE training are transferable to high-speed movements which is pertinent for HSI as these injuries typically occur during high-speed running where the hamstring MTU experiences fast elongation speeds (Askling *et al.*, 2007; Chumanov *et al.*, 2012; Higashihara *et al.*, 2015a; Thelen *et al.*, 2006). Iga and colleagues (2012) also demonstrated that there was no difference between lateral and medial hamstring muscle activation, and activity was at its greatest during the middle phase of the NHE with it remaining high during the last phase of the exercise as the knee adopted a more extended position. Hamstring activation during the NHE and other training exercises will be discussed in more detail later in this chapter. Collectively, the findings show significant improvements in eccentric peak torque and an enhanced ability to resist lengthening with the knee in more extended positions. The findings are pertinent to the more extended knee joint position which occurs during the late swing and early stance phase of sprinting; during which hamstring activity reaches its maximum (Thelen *et al.*, 2005b; Yu *et al.*, 2008) and reported to be vulnerable to injury.

Collectively the literature appears to portray the NHE as a beneficial exercise for hamstring training which offers protective effects to the hamstring muscles to mitigate injury risk (Brooks *et al.*, 2006; MjØlsnes *et al.*, 2004; Peterson *et al.*, 2011; van der Horst *et al.*, 2015). However, HSI commonly occurs during high-speed running (Brooks *et al.,* 2006; Kenneally-Dabrowski *et al.*, 2019b) which is a unilateral activity and thus the bilateral nature of the NHE limits its specificity to the mechanism of injury. The NHE is a single joint exercise and the hamstring muscle-tendon length during the exercise does not reflect the lengths at which high hamstring muscle forces occur during sprinting (Chumanov *et al.*, 2007; 2011). Furthermore, BFlh is the most commonly injured hamstring muscle (Askling *et al.*, 2013; Bourne *et al.*, 2015; Koulouris *et al.*, 2003) and the NHE is reported to generate more ST muscle activation (Bourne *et al.*, 2016; 2017b) and thus its use for BFlh training and mitigation of injury risk may be questioned.

When considering HSI, there are some characteristics of the NHE and its performance that are worthy of consideration and suggest that other exercises may be more appropriate for hamstring training. Orishimo and McHugh (2015) investigated the role of eccentric exercise as part of a four-week strength training programme and its effect on the strength and length tension relationship of the hamstrings. Four exercises were analysed: standing hip extension, standing hip flexion (the diver) a standing spilt exercise (the glider) and the slider exercise. The main findings were that a high level of BFlh, ST and GM peak nEMG amplitude was observed during the exercises with the slider generating higher activity during the eccentric phase. Overall, a 9% gain in knee flexor strength was observed as a result of the four-week training programme, however there was no effect on the length tension relationship as the strength developments were not evident at longer muscle lengths. The latter might be due to the fact that the exercises do not involve concurrent hamstring lengthening across both the hip and the knee joints, with a suggestion that exercises to reduce HSI need to involve near maximal hip flexion combined with knee flexion (Schmitt *et al.*, 2012). The improvement in knee flexor strength was achieved in the absence of using any added weight, thus suggesting that it may be possible to achieve greater increases in strength if external load was added to the exercises analysed. Furthermore, the authors implied that the enhanced strength may have a positive effect on core and lumbo-pelvic control which has been shown to play a role in the reduction of HSI incidence (Askling *et al.*, 2003; Schuermans *et al.*, 2017a; Sherry and Best, 2004).

2.6.3 Eccentric versus isometric training exercises

The hamstring muscles work eccentrically and generate peak activity during the late swing phase of sprinting (Heiderscheit *et al.*, 2005; Higashihara *et al.*, 2016; Schache *et al.*, 2009), thus a number of studies have focused on eccentric exercise to address hamstring training (Askling *et al.*, 2003; 2013; MjØlsnes *et al.*, 2004; Petersen *et al.*, 2011; Seagrave *et al.*, 2014). Recent research however advocates the use of isometric loading in hamstring training programmes as it has been proposed that the contractile element of the hamstring muscles operate in more of an isometric manner during the swing phase of high-speed running and that the increase in muscle-tendon length occurs via the passive element (Chumanov *et al.*, 2007; Thelen *et al.*, 2005a; Van Hooren and Bosch, 2017a). Furthermore, the inability to maintain an isometric action due to high forces being placed on the hamstring muscles during the late swing phase, results in an inefficient eccentric contraction and thus increases the susceptibility of injury (Van Hooren and Bosch, 2017a). Consequently, exercises that emulate this isometric action of the hamstring muscles would appear necessary to encourage training specificity and address hamstring strength. The thoughts presented by Van Hooren and Bosch (2017a) are based on studies investigating the knee extensor and ankle flexor muscles and therefore, while the authors postulate that the same principle of tendon lengthening and isometric muscle fascicle behaviour applies to the hamstring muscles, there is at present no research to substantiate this.

A recent study compared the effects of an isometric single leg Roman chair hold exercise to the NHE on increasing hamstring muscle endurance. During the former exercise, the hamstring muscles work to resist knee extension and attempt to extend the hip (Van Hooren and Bosch, 2017b). After a six-week training programme, superior improvements in strength-endurance were observed as a result of the single leg Roman chair hold exercise in both uninjured and previously injured limbs (Macdonald *et al.*, 2018). Macdonald and colleagues (2018) remarked that the positive results demonstrated with the single leg Roman chair hold exercise may not apply to other isometric exercises, such as the single leg bridge, as the latter includes a pushing component compared to the pull element of the roman chair hold. Hence, the authors acknowledged that their conclusions cannot be extrapolated (Macdonald *et al.*, 2018) thus prompting the need for further research. While acknowledging the latter, the findings presented by Macdonald and co-workers (2018) indicate that the inclusion of both eccentric and isometric based exercises may be advantageous to address muscle endurance, which is a risk factor for HSI (Brooks *et al.*, 2006; Schuermans *et al.*, 2016; Timmins *et al.*, 2016a).

While acknowledging the comment made by Macdonald and colleagues (2018) regarding the single leg bridge, this exercise has been evaluated as a hamstring specific strength endurance test with prospective evidence demonstrating a weaker score being related to an elevated risk of HSI (Freckleton *et al.*, 2014). The latter study advocates the single leg bridge as a screening test for HSI as it places the hamstrings in a position similar to the late swing phase of high-speed running. Consequently, the single leg bridge may serve as a beneficial hamstring exercise to target strength-endurance due to it training the hamstrings in a more functional capacity, however further research is needed to establish this.

2.7 Hamstring muscle activation during training exercises

There is a growing body of research which demonstrates a divergent and selective recruitment of the hamstring muscle in response to training, with different exercises activating different hamstring muscles (Bourne *et al.*, 2017b; Bourne *et al.*, 2018b; Kubota *et al.*, 2007; McAllister *et al.*, 2014; Mendiguchia *et al.*, 2013b; Tsaklis *et al.*, 2015; Zebis *et al.*, 2013) and different parts within the hamstring muscles (Kubota *et al.*, 2007; Mendiguchia *et al.*, 2013a; Schoenfeld *et al.*, 2015). Hamstring strain injuries can occur at different parts of the muscle and often involve different parts of the musculo-tendon complex (Askling *et al.*, 2000; Grange, 2023), therefore knowledge of which exercises maximally activate the hamstring muscles when designing injury prevention and rehabilitation programmes is likely to be beneficial.

The non-uniform activation response to exercise has been proposed to be a consequence of the anatomy and architecture of the individual hamstrings (Kubota *et al.*, 2007; Ono *et al.*, 2010; Ono *et al.*, 2011). The short muscle fibres and large pennation angle of the BFlh suggests that it is more suited to isometric and concentric muscle actions, such as the stance and backswing phase of running. Conversely, ST is composed of longer and thinner muscle fibres with a smaller pennation angle and based on the response of this muscle to eccentric exercise, it has been suggested that it is better able to cope with strain that the hamstrings are exposed to during eccentric movements such as the front swing phase of running (Kubota *et al.*, 2007). The latter is supported by evidence demonstrating that the late swing phase of high-speed running displays the greatest levels of ST activity (Schache *et al.*, 2013). Schuermans and colleagues (2014) report that BFlh plays a compensatory role during eccentric loading as ST lacks the endurance capacity necessary to endure the high loads experienced, thus contributing to BFlh susceptibility to injury. More recent work by the same group of authors reports that ST demonstrated a dominant role during an eccentric prone leg curl exercise and that a divergent pattern of muscle activation is the cause and consequence of HSI (Schuermans *et al.*, 2016). Similar findings of selective ST activation during eccentric knee flexion have been reported (Ono *et al.*, 2010; 2011).

Evidence regarding hamstring muscle activation patterns during different exercises may present a means of addressing the persistently high incidence of HSI. Identifying exercises that generate high hamstring activity and that also preferentially target specific hamstring muscles could serve to improve injury prevention programmes. The next section of this chapter will discuss studies which have investigated hamstring activation in response to training exercises. Prior to reviewing these studies however, it appears pertinent to provide an overview of the two primary methods of analysing muscle activity that have been used such that any differences between them can be considered when the findings of the research are presented and discussed.

2.7.1 Measuring muscle activation - surface electromyography

Surface electromyography is a method used for the recording and analysing the electrical activity produced by active motor units during muscle contraction (Naik, 2012) and is reported as being the gold standard in the assessment of muscle recruitment and activity (Schuermans *et al.*, 2014). Surface electromyography involves the placement of electrodes over muscles and thus offers a safe and non-invasive method to quantify muscle activation and a number of studies have utilised this method to analyse hamstring exercises and provide an insight in to hamstring activation and function (Bourne *at al.*, 2017b; Ono *et al.*, 2011; Schoenfeld *et al.*, 2015; Tsaklis *et al.*, 2015; van den Tillaar *et al.*, 2017; Zebis *et al.*, 2013).

Surface electromyography measures the electrical signals which are generated during muscle contraction under the control of the nervous system (Chowdhury *et al.,* 2013; Reaz *et al.,* 2006) and the signal represents the electrical activity of the motor units of the muscle (Chowdhury *et al.,* 2013; McManus *et al.,* 2020). To develop force and produce movement, signals from the central nervous are sent to the muscle by motor neurons. A motor unit is comprised of a motor neuron and all of the muscle fibres that it innervates (Farina *et al.,* 2016). Once a motor neuron is activated a change in electrical potential, referred to as an action potential, occurs across the membrane of each muscle fibre that is innervated by the motor neuron (Mc Manus *et al.,* 2020). The action potential is propagated into the muscle, stimulating the formation of cross-bridges at the myofibril level. Tension developed in the myofibrils, their respective muscle fibres and motor units is passed through connective tissue (aponeurosis) to tendons. Tendons then transmit force through shortening or lengthening, enabling movement around a joint such as that which occurs during isotonic contractions. Alternatively, a tendon may lengthen with no change in joint position, as per in isometric contractions (Mc Manus *et al.,* 2020; Robertson *et al.,* 2014).

An action potential is a flow of charged particles moving across the membrane of the muscle fibre and the rate of movement of charge represents an electrical current. The electrical currents within a muscle change the electrical potential in the neighbouring tissue and the difference in electrical potential between two points is measured in Volts (V). The voltage distribution measured at the skin as a result of a muscle's electrical activity is captured as the sEMG signal. The latter is the total sum of action potentials generated by motor units which are present within the detection area of the surface electrodes and can be utilised to imply information about motor unit recruitment and muscle activity (McManus *et al.,* 2020). Surface electromyography measures changes in muscle fibre polarity as a consequence of neural excitation. Excitation occurs prior to activation and thus Vigotsky and colleagues (2018) suggest that the term muscle excitation should be used rather than activation, however the plethora of literature pertaining to sEMG studies continue to use muscle activation and was chosen as the term for this thesis.

An unfiltered and unprocessed signal detecting all motor unit action potentials in the sEMG detection area is referred to as a raw EMG signal, and to enable quantitative analysis of the signal certain processing steps need to be employed to increase the validity and reliability of the data (Konrad, 2005). The raw signal contains components of unavoidable noise which may result in inaccurate signal interpretation (De Luca *et al.,* 2010), for example, during dynamic exercise electrode movement may cause a movement artefact which is detected as a signal, but this would be at a frequency outside that of muscle activation. Therefore, filtering is used and is typically performed with a Butterworth fourth order zero lag filter, to ensure sEMG activity remains time aligned to events when it was captured. Full wave rectification is then applied to the raw filtered sEMG data to convert all negative amplitudes to positive values such that parameters including mean, root mean square (RMS), peak and integrated area can extracted to quantify the magnitude of muscle activation. The curve can also be divided into specific time periods relevant to the movement under investigation, allowing activation to be quantified relative to important events during a contraction. Digital smoothing is used to remove noise from the sEMG signal and residual analysis can be applied to increase the accuracy of the filtering process to help maximise the amount of noise removed, without simultaneously removing part of the signal obtained (Winter, 2009). These steps of sEMG signal processing are illustrated in figure 2.2.

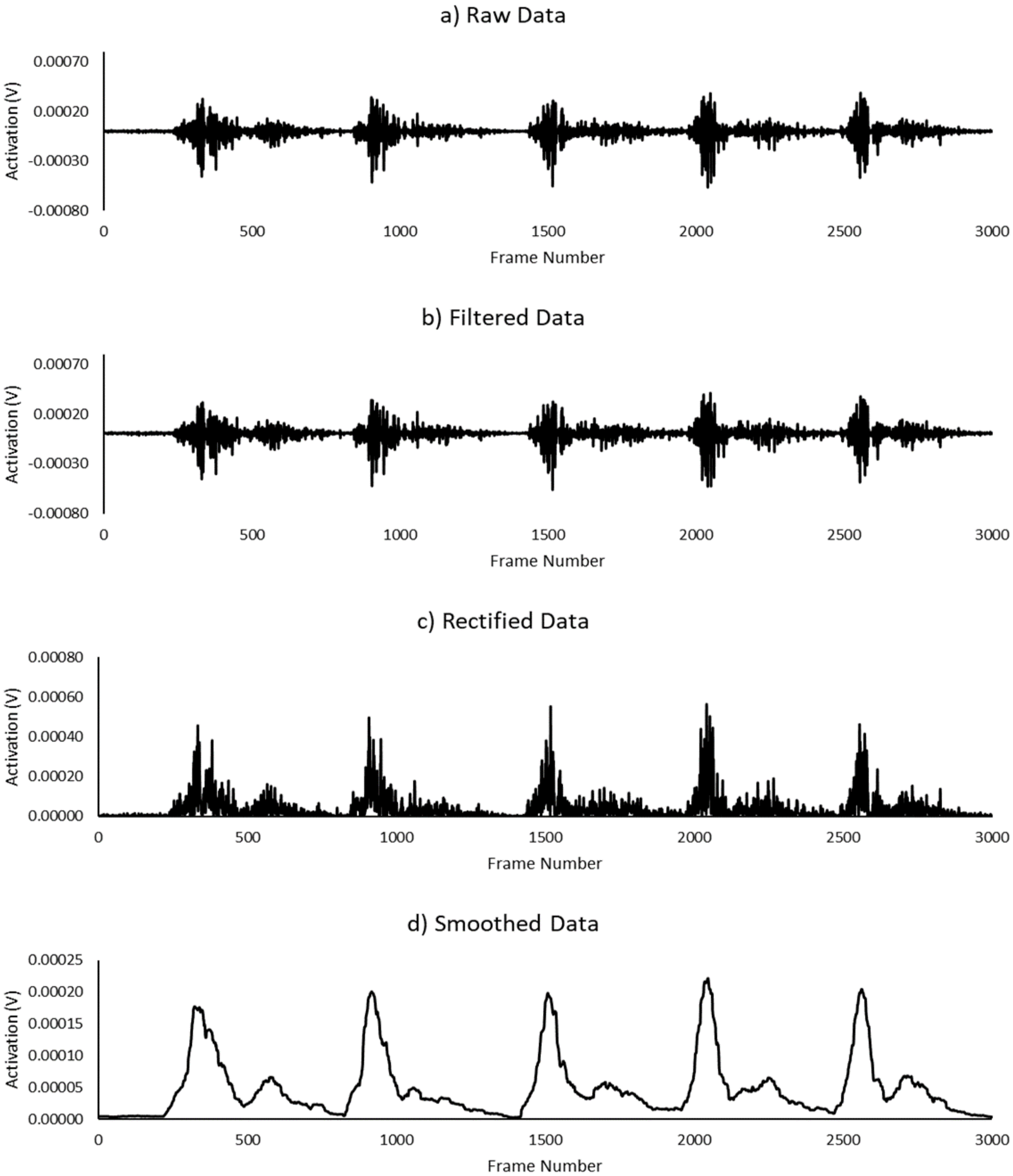

Figure 2.2 Surface electromyography signal processing a) raw data; b) filtered data; c) rectified data and d) smoothed data. This figure represents an example of the data from the data collected for this thesis.

Surface electromyography is a commonly employed method of analysing muscle activity however, there is inherent variability in sEMG measurements. As a means of addressing this matter, standardised guidelines have been established for skin preparation and electrode placement (SENIAM, 2021). Furthermore, to allow reliable comparison of recorded signals using different subjects, muscles and electrode positioning, a normalisation process is encouraged to transform the raw signal to a percentage of the reference value (McManus *et al.,* 2020). There is no gold standard method for normalising sEMG data with some studies using MVIC (Hegyi *et al.,* 2019a; Tsaklis *et al.,* 2015; Zebis *et al.,* 2013) and other studies choosing to adopt dynamic methods (Albertus-Kajee *et al.,* 2011; Prince *et al.,* 2021; van den Tillaar *et al.,* 2017).

The reliability of sEMG measurements of lower limb muscles during isometric and dynamic exercise (Albertus-Kajee *et al.,* 2011; Fauth *et al.,* 2010; Smoliga *et al.,* 2010; Suydham *et al.,* 2017) has previously been reported. The intraclass correlation coefficient (ICC) of peak activity during a MVC has been reported as good (ICC R = > 0.80) for the BF and MG muscles and fair for RF (ICC R = 0.61-0.68) and for sprinting as fair for BF (R = 0.65) and MG (0.60) (Albertus-Kajee *et al.,* 2011). More recently ICC values of > 0.80 have been recorded for lower limb muscles including BF, SM, RF and MG with the authors identifying that the consistency of the peak sEMG was comparable to that observed during a MVIC (Suydam *et al.,* 2017). Fauth and colleagues (2010) analysed the reliability of the quadriceps and hamstrings during MVIC's, a cutting manoeuvre and jump landings and reported ICC's of > 0.80 for the RMS sEMG. The reliability of the RMS during running has been reported by Smoliga and co-authors (2010) with ICC values of 0.98, 0.79 and 0.77 being observed for SM, RF and GM respectively. Smoliga *et al.* (2010) also reported the reliability for iEMG and described ICC's of > 0.80 for SM, RF and GM with the authors concluding that the reliability of iEMG was greater than that of the RMS. Collectively these findings serve to support the use and application of sEMG a means of quantifying muscle activity during physical activity and exercise.

2.7.2 Considerations when using surface electromyography

Motor unit recruitment and rate coding, which is the rate at which action potentials are generated, are elements of sEMG and are parameters that control muscle force (Enoka and Duchateau, 2016; Staudenmann *et al.,* 2010). Consequently, sEMG is often considered to indicate muscle force, however, activation is related to the number of fibres that are active and not the capacity of those muscle fibres to generate force. Higher muscle activity is often inferred to being associated with greater levels of force generation (Vigostsky *et al.,* 2018). While the latter may be the case in isometric contractions (Farina, 2006), muscle force at a given level of muscle activity is affected by a range of factors not reflected in the EMG signal, including muscle length, contraction type and muscle and tendon structure (Staudenmann *et al.,* 2010; Vigotsky *et al.,* 2018). For example, an eccentric contraction will require less activation to generate a given amount of force when compared to a concentric or isometric contraction (Herzog *et al.,* 2015). Similarly, as force varies with muscle-tendon length, the amount of activation necessary to generate force at different joint angles is likely to vary. Activation and force vary in several ways, including the fact that activation discounts the passive elements and deals only with active contributions to force (Vigotsky *et al.,* 2018). Therefore, the amount of storage and release of energy in tendons, generating to force production capabilities during dynamic tasks such as sprinting, will also not be captured by sEMG.

Surface electromyography is able to provide information regarding the timing of excitation (temporal element) and the amount of excitation (spatial element) of muscles in real time (Cagnie *et al.*, 2011). However, it has inherent limitations including the movement of the electrodes relative to the skin and muscle fibres, and cross talk from neighbouring muscles which distorts the signal and can result in the incorrect interpretation of the recorded signal (De Luca *et al.,* 2010; 2012). The amount of cross talk is influenced by the inter-electrode distance with a smaller distance resulting in less crosstalk signals; and also, the sensor location on the muscle as less crosstalk is detected when the electrode is placed in the middle of the muscle belly (De Luca *et al.,* 2010). While acknowledging this information, sEMG continues to be a useful method for analysing and providing insight into the neuromuscular system (Vigotsky *et al.*, 2018; McManus *et al.,* 2020) and results from studies utilising sEMG can contribute to the knowledge regarding exercise selection for HSI prevention strategies.

2.7.3 Measuring muscle activation - Functional magnetic resonance imaging

Functional magnetic resonance imaging (fMRI) offers a non-invasive way of measuring changes in muscle physiology after exercise (Cagnie *et al.*, 2011). There is evidence of increasing use of fMRI as a technique to analyse hamstring exercises and measure the metabolic activity of muscles (Bourne *et al.*, 2017b; Bourne *et al.*, 2018b; Mendiguchia *et al.*, 2013a) as it provides heightened spatial clarity, which results in high quality muscle imaging and detailed anatomical information which sEMG is unable to offer (Cagnie *et al.*, 2011; Kubota *et al.*, 2009). While fMRI is not influenced by signal crosstalk or impedance from electrode placement; it is limited by the fact that it is a modality that cannot be used during activity or exercise. Furthermore, the large cost of fMRI (Bourne *et al.*, 2017b) may limit access to it and thus makes sEMG a more accessible method of analysing muscle activation patterns.

2.7.4 Hamstring muscle activity – implications for exercise selection

The next section of this chapter will predominantly focus on studies which have utilised sEMG to investigate hamstring activation during training exercises, however fMRI studies will also be acknowledged as the findings contribute to the current evidence base regarding the patterns of hamstring muscle activity during different exercises. The aforementioned differences between these two methods will however require consideration during the discussion of the findings of various studies. Table 2.4 illustrates the characteristics of studies which have investigated hamstring activity during different training exercises.

Table 2.4 Study characteristics investigating hamstring muscle activity during different training exercises

Authors	Sample	Method	Exercises	Load	Findings
Bourne *et al.* (2017b)	24 recreationally active men	Surface electrodes & fMRI	Glute-ham raise, lunge, NHE, prone leg unilateral bent & straight knee bridge, hip hinge, 45° hip extension, unilateral & bilateral stiff leg deadlift	12RM	Hip extension exercises recruit BFlh & NHE recruits ST. Even BFlh & medial hamstring activity during bridge exercise.
Hegyi *et al.* (2018)	12 recreationally active men	High-density surface electrodes	NHE and stiff-leg deadlift	Body weight NHE 80% 1RM deadlift	BFlh activity during NHE was highest in proximal region & lowest in distal region. During the deadlift, BFlh activity was similar in middle & distal regions & lowest in proximal. ST activity highest in middle region for NHE & deadlift. Overall ST activity higher than BFlh activity during NHE. Negligible difference during deadlift.
Hegyi *et al.* (2019a)	19 amateur males (9 soccer players, 6 Gaelic football, 4 rugby players)	High-density surface electrodes	Good morning, prone leg curl, slide leg curl, cable pendulum, unilateral Romanian deadlift (RDL), bent-knee bridge, 45° hip extension, straight knee bridge, upright hip extension conic pulley	12RM	BFlh activity only higher than ST during 45° hip extension. Similar BFlh & ST activity during bridge exercises. ST activity significantly higher than BFlh during prone leg curl (concentric phase). Regional hamstring activity was affected by contraction mode.
McAllister *et al.* (2014)	12 weight trained men	Surface electrodes	Glute-ham raise, good morning, prone leg curl & RDL	85% 1RM	More BFlh, ST & SM activity curl & RDL during eccentric RDL. More BFlh activity during eccentric good morning than prone leg curl. More medial hamstring activity during eccentric phase of good morning. Concentric hamstring activity highest during glute-ham raise. Gastrocnemius activity higher for RDL than prone curl.

Authors	Sample	Method	Exercises	Load	Findings
Ono *et al.* (2010)	7 healthy, untrained males	Surface electrodes and fMRI	Eccentric prone leg curl Concentric & eccentric prone leg curl	120% 1RM 50% 1RM	Selective ST activation. Selective ST activation.
Ono *et al.* (2011)	6 healthy, untrained males	Surface electrodes and fMRI	Stiff leg dead lift	60% body weight	Selective BFlh & SM activity compared to ST during eccentric & concentric phases.
Schoenfeld *et al.* (2015)	10 male students	Surface electrodes	Stiff leg deadlift, prone leg curl	8RM	Higher lower lateral & lower medial hamstring activity during prone leg curl. Similar activity of upper lateral & upper medial hamstrings during prone leg curl & stiff leg deadlift. Upper lateral hamstring activity higher than lower lateral during deadlift & a trend for higher medial hamstring activity compared to lower medial.
Tsaklis *et al.* (2015)	20 female elite track & field athletes	Surface electrodes	Lunge, single leg RDL, NHE, kettle bell swing, single leg bridge, TRX exercise, hamstring bridge, standing curl, slide leg, fitball flexion	12kg kettle bell, curl with resistance band <2kg, lunge with bar (weight not stated)	More ST activity during low intensity (<50% MVIC) exercises = lunge, RDL & kettle bell swing. Medium intensity (≥ 50% or < 80% MVIC) = TRX, hamstring bridge, standing curl. High intensity (>80% MVIC) = NHE, slide leg & fitball exercise. More BFlh activity during fitball.
van den Tillaar *et al.* (2017)	12 male sports students	Surface electrodes	Laying kick, standing kick, NHE, NHE with return, NHE with bump, cranes & cranes with return	Body weight	Maximum BFlh & ST activity greater during sprinting vs. exercises. Maximal BFlh & ST activity lower during cranes compared to the NHE exercises. SM activity higher during laying kick vs. standing kick & crane exercises. SM activity during cranes lower than NHE.
Zebis *et al.* (2013)	16 females (8 handball and 8 elite soccer players)	Surface electrodes	Kettle bell swing, NHE, supine one leg curl, seated leg curl, prone leg curl, supine pelvis lift, RDL, hyperextensions (body weight & barbell)	Kettle bell 12kg or 16kg, IKD for leg curls, RDL 12RM, hyperextension barbell 13.3kg	More ST activity during RDL & kettlebell swing compared to BFlh. More BFlh activity during supine leg curl.

RM = repetition maximum; fMRI = functional magnetic resonance imaging; MVIC = maximal voluntary isometric contraction; IKD = isokinetic dynamometer

Recognising the prevalence of HSI in sport, Tsaklis and colleagues (2015) analysed the patterns of the hamstring muscle activation during a range of exercises as a means of determining which exercises would be better for hamstring injury rehabilitation. The authors categorised the exercise intensity based on the percentage of the maximal voluntary isometric contraction (MVIC); low (<50% MVIC), medium (>50% or <80% MVIC), or high intensity (>80% MVIC). Additionally, changes in the MTU length were reported and when peak activity occurred, however the type of muscle contraction was not identified. The majority of the low intensity, closed chain exercises (lunge, Romanian dead-lift T drop, and kettle bell swings) demonstrated greater ST activation compared to BFlh (Tsaklis *et al.*, 2015). Similar findings of ST activity during a single leg deadlift and kettle bell swing exercise have previously been reported (Zebis *et al.*, 2013). Conversely, Mendiguchia and colleagues (2013a) observed preferential involvement of the upper part of the BFlh muscle during a lunge – these conflicting findings may be explained by the fact that the latter study used fMRI rather than sEMG.

The greater ST activation observed (Tsaklis *et al.*, 2015; Zebis *et al.*, 2013) may be a result of the muscle's anatomical configuration as it is a fusiform muscle with long fibres and a large number of sarcomeres in series (Woodley and Mercer, 2005), and thus may demonstrate a more sensitive response to exercises which require hip flexion and a large change in muscle-tendon length (Zebis *et al.*, 2013). Furthermore, it has been reported that ST has a larger excursion capacity when compared to BFlh and SM (Kellis *et al.*, 2012). Consequently, the ST muscle's velocity of contraction is increased and it is able to shorten over long distances when it is stretched (Ono *et al.*, 2010), such as during the deadlift and kettle bell swing where hip flexion is required. Collectively, these findings suggest that exercises requiring hip flexion in a standing position preferentially activate ST as measured via sEMG.

The single leg bridge is used to assess hamstring strength with evidence suggesting that a weaker test score demonstrates reduced hamstring strength-endurance and a greater risk of HSI (Freckleton *et al.*, 2014). Tsaklis and colleagues (2015) investigated muscle activation during a single leg bridge and a bilateral hamstring bridge, with the former having the foot on the floor, and the latter with feet elevated on a chair. No preferential hamstring activity was observed during either exercise however the single leg bridge was described as being a low intensity exercise (<50% MVIC) and the bilateral hamstring bridge a medium intensity exercise

(≥50% or <80% MVIC). Therefore, while there was no evidence of hamstring bias, these findings show how altering the limb position can increase hamstring muscle amplitude during a bridging exercise.

Earlier work by Andersen and colleagues (2006) and Zebis *et al.* (2013) analysed a single leg bridge, as used by Tsaklis and co-workers (2015), and report similar findings of homogenous hamstring activity, however there was variation in the mean normalised peak amplitude of the individual hamstring muscles. In particular, Andersen and colleagues (2006) reported lower peak amplitude when compared to Zebis *et al.* (2013) and Tsaklis and co-workers (2015). Such findings may be a consequence of the background of the participants as those included in the study completed by Andersen *et al.* (2006) had no experience of resistance training while the other two aforementioned studies involved elite athletes. Neural adaptations in response to strength training allows improved activation of agonist muscles (Sale, 1988) and therefore may explain in the discrepancy in findings with regards to the peak amplitudes of muscle activity in these studies.

The aforementioned studies adopted a bridge exercise with the knee positioned in 90° flexion. Bourne and colleagues (2017b) analysed muscle activation during a straight knee and bent knee bridge and reported that the exercises generated a high level of hamstring activation and that there were no significant differences between hamstring muscle activity. Furthermore, the authors also concluded that hamstring activity does not vary significantly between contraction types during a bridge exercise. There appeared to be a trend for higher BFlh activity during the straight knee bridge while the bent knee bridge appeared to generate more selective recruitment of the ST muscle. These observations were described as being related to the larger moment arm of the BFlh and ST muscles at the hip and knee joint respectively (Bourne *et al.*, 2017b).

Findings presented by Hegyi and co-workers (2019a) mirror those of Bourne and colleagues (2017b) regarding relatively even hamstring muscle activity during a straight knee bridge. During the bent knee bridge, small, yet significant differences were evident between BFlh and ST activity during the concentric phase of the exercise however, no between muscle differences were evident in the eccentric phase (Hegyi *et al.*, 2019a). The knee joint position was not specified by Bourne and colleagues (2017b) and Hegyi and co-workers (2019a) however the illustrations of the exercises imply that for the straight knee bridge there was some degree of flexion rather than the knee being fully extended, and for the bent knee bridge the knee was flexed to a minimum of 90° which mirrors the position adopted by other studies (Tsaklis *et al.*, 2015; Zebis *et al.*, 2013). The two latter studies did not differentiate between the phases of the exercises and rather analysed overall muscle activity during the bridge and thus influences direct comparison to Bourne and colleagues (2017b) and Hegyi and co-workers (2019a).

A preferential recruitment of the ST muscle and a selective recruitment of BFlh compared to BFsh has been observed during a single leg bridge via fMRI and has been suggested to be a possible consequence of hamstring anatomy (Bourne *et al.*, 2018b). The hamstrings have to resist shearing forces at the knee joint during the single leg bridge and as the sagittal plane moment arm of the ST is greater at the knee when compared to the SM and BF (Thelen *et al.*, 2005b), it has a key role in limiting anterior tibial translation. Furthermore, the ST is a long, thin fusiform muscle with many sarcomeres in series which may be better suited to muscle contractions at longer lengths (Ono *et al.*, 2011), which may influence the observed higher incidence of BFlh injury during sprinting. While detail regarding the knee position was not provided (Bourne *et al.*, 2018b), the illustration provided depicts little knee flexion and thus it seems appropriate to categorise the exercise as a straight knee bridge when compared to other published work (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a). Collectively the findings demonstrate that the bridge exercise generates a high degree of hamstring muscle activation and that when the knee is in more of an extended position the magnitude of activation is greater (Bourne *et al.*, 2017b; 2018a; Hegyi *et al.*, 2019a). The use of fMRI may have influenced the finding of preferential ST activation when compared to sEMG studies (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a; Zebis *et al.*, 2013). Knowledge of a preferential recruitment of the ST muscle may offer beneficial effects for hamstring training and injury prevention programmes, however further research is needed to clarify this (Schuermans *et al.*, 2014; 2016).

The medium intensity exercises (TRX, Nordic curl and leg curl; ≥50% or <80% MVIC) identified by Tsaklis and colleagues (2015) did not demonstrate any bias with regards to ST and BFlh activation. Comparable findings of similar hamstring activity during a prone leg curl exercise have previously been reported (Zebis *et al.*, 2013) while others report preferential ST activation during this exercise (Bourne *et al.*, 2017b). The latter study differentiated between the concentric and eccentric phases of the prone leg curl while the earlier studies did not and this may contribute to the discrepancy in findings. Furthermore, the use of female (Tsaklis *et al.*, 2015; Zebis *et al.*, 2013) versus male participants (Bourne *et al.*, 2017b) and the use of sEMG and fMRI in the latter study require consideration as these may have contributed to the different findings.

In line with the findings of Tsaklis and colleagues (2015), a lack of preferential activity between the medial and lateral hamstrings during the NHE has been reported previously (Iga *et al.*, 2012; van den Tillaar *et al.*, 2017; Zebis *et al.*, 2013) while others report selective ST recruitment compared to the other hamstring muscles during the NHE (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a). Functional magnetic resonance imaging studies have also demonstrated that the NHE generates greater ST activity (Bourne *et al.*, 2016; 2017a; Mendiguchia *et al.*, 2013b). The long, thin and fusiform structure of the ST is likely to influence the muscle's contribution during the NHE, as evidenced in recent studies (Bourne *et al.*, 2016 and Mendiguchia *et al.*, 2013b) as its arrangement enhances its ability to cope with the strain experienced during the NHE (Ono *et al.*, 2011). It has also been proposed that the selective activation of the BFsh muscle during the NHE is a result of the muscle's morphology and architecture. This muscle only crosses the knee joint and when compared to the remaining hamstring muscles it has the smallest cross-sectional area (Woodley and Mercer, 2005) which enables it to cope with the strain of the NHE (Mendiguchia *et al.*, 2013b). This body of research findings suggests that the response of the hamstring muscles to exercise is likely to be influenced by the architecture of individual muscles and the tools of measurement used to monitor the outcome.

The slide leg exercise was categorised as a high intensity (> 80% MVIC) exercise by Tsaklis and colleagues (2015) which mirrors the supine leg curl analysed by Zebis and co-workers (2013), who also observed high hamstring activity during this exercise. Both exercises are similar to the slider exercise with regards to hip and knee movement however, they involve single leg movement through concentric and eccentric phases of the exercise while the slider has double leg support during the concentric phase (Orishimo and McHugh, 2015). Irrespective of the difference between the exercises, the aforementioned studies concur that they generate high peak amplitude of normalised EMG (nEMG) of the hamstring muscles. Zebis and co-workers (2013) reported a significantly higher BFlh amplitude compared to ST during the supine leg curl while no evidence of preferential hamstring excitation was observed by Tsaklis and colleagues (2015), which mirrors the findings of Orishimo and McHugh (2015). Zebis and co-workers (2013) detailed the training history of their participants, including 4.7 ± 0.7 sessions per week, 15.6 ± 4.1 years participation in their sport and 5.4 ± 2.4 years in strength and conditioning. Tsaklis and colleagues (2015) and Orishimo and McHugh (2015) did not provide the training background of their participants and this may be a contributing factor to the disparity in findings.

Tsaklis *et al.* (2015) observed that the fitball flexion exercise resulted in a greater activation of BFlh when compared to ST and is an exercise that requires alternate knee flexion using body weight, and therefore differs to the prone curl which has been investigated in other work. Zebis and colleagues (2013) observed a bias towards to BFlh activation during a single leg prone hamstring curl exercise, but this finding lacked significance. Findings of high hamstring activity has also been reported by Hegyi and colleagues (2019a) during a double leg prone leg curl. Both of these exercises place the hip in a neutral position and are therefore knee dominant in nature. Hip dominant exercises appear to selectively recruit the BFlh muscle. Zebis and colleagues (2013) report greater BFlh activity during exercises that are hip dominant including hip hyperextension; similar findings have been reported for other hip biased exercises including the stiff leg deadlift (Ono *et al.*, 2011) and 45° hip extension exercise (Bourne *et al.*, 2017b). Collectively, these findings suggest that hip extension exercises may be the best choice when targeting BFlh activation and strength. The influence of hip dominant exercises on BFlh activity may be linked to the muscle's larger moment arm at the hip which causes a greater change in the muscle as the position of the hip alters (Mendiguchia *et al.*, 2013b).

Conversely to the studies reporting selective BFlh activation during hip dominant exercises, McAllister and co-workers (2014) observed a preferential activity of ST in both knee (prone leg curl and glute-ham raise) and hip dominant exercises (good morning and Romanian deadlift). McAllister and colleagues (2014) did not provide any information regarding normalisation of their data, which, based on their data being collected over a number of days, influences direct comparison (De Luca, 1997). The background of the participants used in these particular studies varied and thus may influence the different results obtained due to differing training experience and familiarisation with the exercises performed. Participants included weight trained men (McAllister *et al.*, 2014), female elite athletes (Tsaklis *et al.*, 2015), female soccer players (Zebis *et al.*, 2013), male national level soccer referees (Mendiguchia *et al.*, 2013b) and recreational male athletes (Bourne *et al.*, 2017a). The tools used for data collection also require consideration, namely the use of sEMG (Iga *et al.*, 2012; McAllister *et al.*, 2014; Tsaklis *et al.*, 2015; Zebis *et al.*, 2013) compared to fMRI (Mendiguchia *et al.*, 2013b; Bourne *et al.*, 2015; Bourne *et al.*, 2016) compared to using both sEMG and fMRI (Bourne *et al.*, 2017b; Ono *et al.*, 2010; Ono *et al.*, 2011).

Bourne and colleagues (2017b) analysed the nEMG amplitude and ratio of lateral versus medial hamstring activity in 18 recreational male athletes during 10 strength training exercises. In addition to the sEMG data accumulated, further data from 10 athletes was collected via fMRI to determine the patterns of hamstring activation during the exercises that least, and most selectively targeted the BFlh as demonstrated via the sEMG. Collectively, the findings showed that during eccentric contractions, the BFlh was selectively activated during the 45° hip extension, while the NHE resulted in the least selective activation. Conversely, the ST was preferentially recruited during the NHE. With the BFlh being the most commonly injured hamstring muscle (Koulouris and Connell, 2003; Bourne *et al.*, 2015), the bias towards ST activation may question the role of this exercise in addressing BFlh injury. The data obtained by Bourne *et al.* (2017b) however revealed that the NHE resulted in the highest eccentric BFlh activity compared to all other exercises analysed, and previous work has also reported high BFlh activity during the NHE (van den Tillaar *et al.*, 2017; Zebis *et al.*, 2013). Therefore, this exercise may be of use when trying to mediate HSI risk via higher muscle activation, however the lack of hip movement may limit the effectiveness of the NHE.

Eccentric strength training at longer muscle-tendon lengths has been proposed as a means of mirroring the concurrent movements at the hip and knee during sprinting (Schache *et al.*, 2012). The latter has been confirmed in a recent study by van den Tillaar and co-workers (2017) who observed that the NHE and three variations of the exercise resulted in high hamstring activation at hip and knee angles that are similar to those during which peak activity occurs during maximal velocity high-speed running. The latter study analysed hamstring muscle activation using a non-motorised treadmill and this requires some consideration as evidence regarding reported differences in treadmill versus overground running are inconclusive (Chumanov *et al.*, 2011; Schache *et al.*, 2011; Wang *et al.*, 2014). Furthermore, van den Tillaar and colleagues (2017) did not differentiate between the phases of the running gait cycle and thus when referring to the hip and knee joint angles of the exercises did not state during what part of high-speed running these angles corresponded to. The latter would have been beneficial to determine if the lower limb joint angles and associated high muscle activation were aligned to the early stance and late swing phases of high-speed running during which HSI is commonly reported to occur.

2.8 Clinical implications

There is conflicting evidence with regards to hamstring muscle activation during traditional hamstring training exercises, with literature suggesting inter-muscular hamstring differences and that different contraction modes of an exercise can result in distinctive patterns of muscular activation. The clinical relevance of understanding hamstring activation during different exercises is related to the relatively unchanged incidence of HSI and re-injury rates which have shown no improvement during the last three decades (Ekstrand *et al.*, 2011; 2016), thus questioning the effectiveness of current injury prevention and rehabilitation programmes.

Hamstring training interventions should address the risk factors identified for HSI in an attempt to mitigate injury risk. While the role of individual hamstrings in HSI is yet to be determined, neuromuscular coordination and balanced strengthening of these muscles is advocated (Hegyi *et al.*, 2019a Schuermans *et al.*, 2014), with exercises which generate high overall activity being recommended to encourage muscle adaptations (Hegyi *et al.*, 2019a). In conjunction with the latter, considering the mechanism of injury is important as this can encourage the specificity of exercise by considering the limb position and demands placed on the hamstring muscles.

2.9 Summary

There is a high prevalence of HSI in sprinting-based sports, including rugby union codes, which can result in prolonged absence from training and competition and financial implications for sports teams and clubs. There is some debate with regards to when HSI occurs during sprinting, however, early stance and late swing or the transition between these two phases being proposed as the injury risk phases of the gait cycle. The majority of evidence illustrates the late swing phase as the period during which HSI most frequently occurs, which is when peak hamstring length and activity is evident. In particular the BFlh encounters the highest musculotendon stretch and strain during late swing, which may explain its propensity to injury when compared to the remaining muscles in the hamstring group.

Hamstring strain injury is multifactorial in nature with a number of identified risk factors including decreased muscle strength and neuromuscular co-ordination, which can be addressed via hamstring training programmes. Evidence for the use of eccentric exercise, in particular the NHE, for training and HSI prevention is well established, however other exercises are worthy of investigation. There is a growing body of evidence demonstrating heterogenous hamstring activity across different exercises. Specifically, there is research which identifies that BF and ST respond differently to different exercises with some generating higher activation than others. Furthermore, there is evidence showing selective BFlh activation during hip extension-based exercises while knee biased exercises seem to target the ST muscle to a greater extent. Knowledge pertaining to hamstring muscle activation patterns in response to strength training exercise has the potential to influence exercise selection and may have implications for HSI prevention practices. To date, few studies have examined muscle activation patterns during sprinting and hamstring training exercises in rugby players, thus implying the need for further research.

Chapter 3

Methods

3.1 Experimental procedures

All participants were high-level rugby players and each visited the National Indoor Athletics Centre (NIAC) at the School of Sport and Health Sciences, Cardiff Metropolitan University for testing. All participants were asked not to consume alcohol and to rest from training for 48 hours prior to taking part to minimise the potential impact of fatigue on test performance. The height of participants was measured using a stadiometer (Seca 213, Seca, Hamburg, Germany) and mass measured using digital scales (Seca 7701321004, Seca, Hamburg, Germany). All participants completed a 20-minute standardised, supervised warm-up which was devised in conjunction with the strength and conditioning coach of the rugby team. All participants were familiar with the content of the warm-up which included jogging two laps of the 200 m indoor track in NIAC at a self-elected speed, dynamic exercises, three sprints of progressive intensity (70%, 80% and 90%) over 50 metres (m) and dynamic stretching of all lower limb muscle groups. All participants wore their own trainers, socks, shorts and vests for data collection procedures. After completing the warm-up, sEMG electrodes were affixed to the lower limb and muscle activity was recorded during sprinting and hamstring exercises as outlined below. All sprint and exercise trials were video recorded to determine a stride in the maximal velocity phase and to identify the start and end of each repetition respectively.

3.1.1 Sprinting protocol

All sprint trials took place on an indoor synthetic running track (Mondo, Warwickshire, UK) in the NIAC at the School of Sport and Health Sciences, Cardiff Metropolitan University. The maximal velocity phase of the sprinting trials was determined for each participant (30 – 40 m) as this was the window of interest with regards to lower limb muscle activity. Five minutes rest was provided in between each running trial to minimise the effects of fatigue (van den Tillaar *et al.*, 2017).

a) Studies 1, 2 and 3

The sprinting protocol for study 1 involved participants completing 3 x 40 m sprint trials. Smartspeed timing gates (Smartspeed, Fusion Sport) were used at 10 m intervals to provide 10 m split times and the total time to complete the sprint trial. The timing gates also served as markers for the total distance to be covered. Players started each trial from a stationary, split standing (crouched) position (Higham *et al.*, 2013; Ross *et al.*, 2015) with the lead foot behind a line taped on the floor 50 cm behind the first timing gate placed at 0 m. The first timing gate was set at a height of 1 m to avoid the beam being broken too early by the upper body, while the remaining gates were set at 1.2 m. Muscle activity was recorded during all sprinting trials and all trials were captured using a panning video camera (Sony HDR-Z5E, Sony, Japan) at a capture rate of 100 frames per second. The video data of the sprinting trials was used to identify the first stride of the test limb during the maximal velocity phase (30 – 40m) of each sprint and was synchronised with the sEMG data recorded during the sprint trials. The data collected was also used for studies 2 and 3 (chapters 5 and 6).

b) Study 4

The sprinting protocol for study 4 involved participants completing 3 x 50 m running trials. A laser distance meter (type LMC-J-0310 Sport) (LOKE engineering, Kempf GmbH & Co., Waldorf Germany) was used to quantify running speed and to identify the split and total time frames for the 50 m sprint trials using a sampling rate of 100 Hz. The origin for the laser was the start line (0 m) and players started each sprint trial from a stationary, split standing (crouched) position (Higham *et al.*, 2013; Ross *et al.*, 2015) at a distance of 5 m away from the laser distance metre. Surface electromyography was collected during all sprint trials and the 30 – 40 m window of all trials were captured using two cameras (Vicon Vue, Vicon Motion Systems Ltd., Oxford, UK) at a capture rate of 100 frames per second to determine one stride of the gait cycle. A 50 m distance set-out for the sprinting trials and the laser data confirmed all participants achieved max velocity within 30 - 40 m.

For the purpose of analysing muscle activity during sprinting, the sprint cycle was divided in to four phases based on a method previously used by Howard and colleagues (2018):

1. Early stance – this phase starts as the foot makes initial ground contact and ends at the mid-stance phase, estimated at 0-15% of the sprint cycle.

2. Late stance – this phase starts at the mid-stance phase and ends at toe off, estimated at 15-30% of the sprint cycle.
3. Early and mid-swing – this phase starts at toe off and ends two thirds of the way through the swing phase, estimated at 30-77% of the sprint cycle.
4. Late swing – this phase starts at two thirds of the way through the swing phase and ends at initial ground contact, estimated at 77-100% of the sprint cycle.

The first stride which occurred within the maximal velocity phase (30 – 40m) was used for data analysis. The video data was used to visually determine foot contact, toe off and ipsilateral foot contact and these events denoted one stride. The frame numbers for these events and the difference in the number of frames between events were used to calculate mid-stance, early and mid-swing and late swing phases accordingly using the method presented by Howard and colleagues (2018).

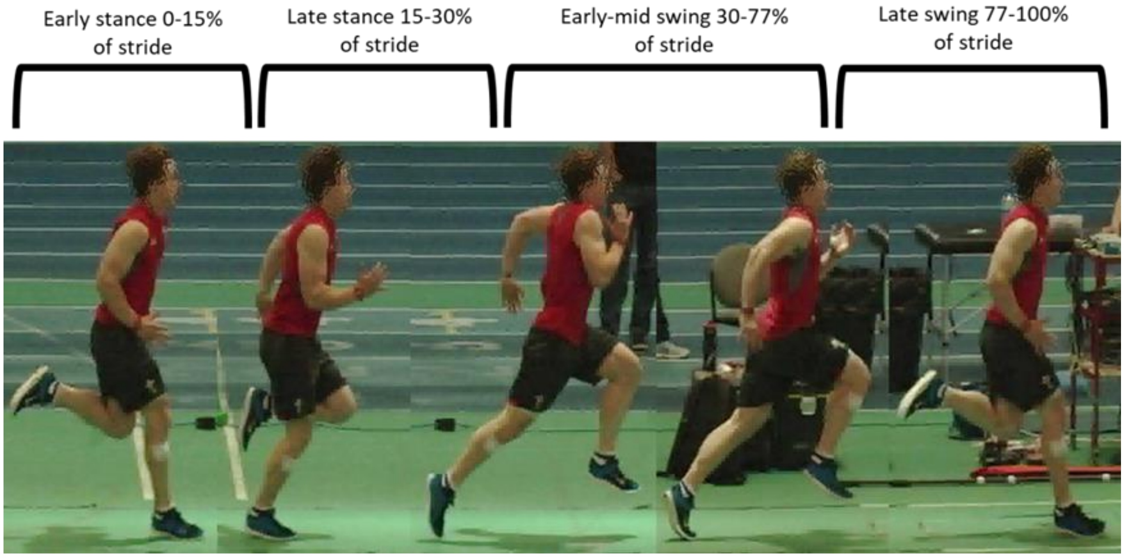

Figure 3.1 Phases of the sprinting gait cycle

3.1.2 Exercise Protocol

The exercises chosen for the purpose of this thesis are based on the review of literature presented in chapter 2 in conjunction with clinical practice and experience. The single leg Roman chair exercise in particular was chosen due to personal experience of using the exercise in the clinical environment and to contribute to the evidence base, which compared to the other exercise chosen, is minimal at the time or writing this thesis.

A 10-minute rest period was provided after the sprint trials before the exercise protocol was started. All exercises were performed in a random order to remove bias and to reduce any order of effect due to fatigue. To minimise any influence of fatigue on the muscles being analysed a low number of repetitions were used and five minutes rest was provided in between each exercise (McAllister *et al.*, 2014; Tsaklis *et al.*, 2015). The researcher provided a verbal explanation and practical demonstration of all exercises to the participants prior to the start of data collection to ensure that they understood what the exercises entailed.

Based on their training history, participants were familiar with all exercises other than the slider (Study 2) and the single leg Roman chair hold (Study 4). Participants were given the opportunity to complete one practice repetition of each exercise prior to the test repetitions. Feedback was provided to participants during all exercises to ensure correct technique. If a participant made an error, then the exercise was stopped and a three-minute rest period was given and the exercise was performed again (Tsaklis *et al.*, 2015). During all exercise trials, video data was recorded in the sagittal plane and sEMG data collected for each muscle accordingly. The video data was used to identify the start and end of the exercise repetitions.

Studies 2 and 3

The exercises analysed included the NHE, single leg prone hamstring curl, single leg bridge, the slider, single leg Roman chair hold (body weight) and single leg Roman chair hold (20kg bar). Two repetitions were performed for each of the six exercises, with five minutes rest provided between each exercise. The exercise intensity varied depending on the nature of the exercises with one using an IKD, one including the addition of an external load and the remaining being performed with body weight. The elite level of the participants in these studies and their busy training and playing schedule meant that there was a desire to ensure the management of load and player safety. This was achieved by controlling the total dosage and load that players were exposed via the number of repetitions (2 repetitions) completed per exercise (6 exercises), which equated to a total of 12 repetitions. The latter was considered to add limited additional training load to the participants schedules.

Study 4

The exercises analysed include the double leg prone hamstring curl, single leg bridge and single leg Roman chair hold. Five repetitions (Oliver and Dougherty, 2009) of the three exercises were performed using three progressive loads per exercise, with two minutes rest provided between each set of five repetitions and a five-minute rest was provided between each exercise (McAllister *et al.*, 2014; Tsaklis *et al.*, 2015). The use of a higher number of repetitions in this study was desirable to encourage a more reliable measure and was made possible due to the recruitment of participants from a university rugby team compared to the international level rugby players included in studies 2 and 3 (Chapter 4 and 5). As the exercise protocol included the completion of each exercise under three different loading conditions, a total number of five repetitions was chosen to minimise the effects of fatigue. The loads were calculated as a percentage of participant body weight with the percentage being determined based on the requirements of each exercise, including double versus single limb, body position and inclusion of isometric holds per repetition. In addition to the latter, pilot work with a sub-sample of participants was further used to determine the upper limit of each load analysed. The loads used were as follows:

a) Double leg prone hamstring curl 20%, 35% and 50% of body weight

b) Single leg bridge 5%, 15% and 25% of body weight

c) Single leg Roman chair hold 10%, 20% and 30% of body weight

1) Nordic Hamstring exercise

This exercise was adopted from MjØlsnes *et al.* (2004) and Ditrolio *et al.* (2013). The participants started in a kneeling position on the floor with the torso held in a straight and rigid position with their arms held across their chest and hands on their shoulders. A partner applied pressure on the lower legs to make sure that the participant’s feet stayed in contact with the ground throughout the exercise. The participant was instructed to keep their hips fixed and to lower their upper body to the ground as slowly as possible by extending the knees and trying to resist the fall by contracting the hamstring muscles. The participant was asked to use their hands to break the forward fall, letting the chest touch the floor and immediately get back to the starting position by pushing with their hands to minimise loading in the concentric phase. The second repetition was performed as soon as the participant returned to the starting position and both repetitions were completed using body weight. The speed of each repetition was self-selected as the exercise is influenced by the participant's ability to control the forward movement of the upper body.

Figure 3.2 Nordic Hamstring exercise

2) Slider exercise

This exercise was adopted from Orishimo and McHugh (2015). At the start of the exercise participants laid down in a supine position on a slide board. Each participant performed a single leg bridge and then lowered themselves to the floor by extending the knee of the supporting, test leg and sliding the heel forward. While the torso remained on the floor, both feet were then used to flex both knees and lift into the single bridge, starting position. This method meant that the participants completed the eccentric action through a full range of movement and that minimal concentric action was performed. Each repetition was performed using body weight and took six seconds to complete - two second bridge, two second knee extension, two second knee flexion – and the researcher verbally counted the six seconds to control the speed of the exercise.

Figure 3.3 The slider exercise

3) Prone hamstring curl

a) Studies 2 and 3

The single leg prone hamstring curl was adopted from Zebis and co-workers (2013). Participants laid in a prone position on the isokinetic dynamometer with the axis of rotation on the lever arm being at the centre of the knee joint of the test limb and the knee fully extended. The lever arm of the dynamometer was attached superior to the lateral malleolus of the ankle joint, and straps were used to stabilise the trunk and pelvis of the participants. Knee range of motion was fixed at 100° of flexion from the maximum active knee extension (0°). While holding on to the handles on either side of the isokinetic dynamometer the participants were instructed to flex and extend their knee fully against the resistance of the dynamometer and encouraged to avoid any rotation of the limb.

Before the actual test trials, participants performed three practice concentric and eccentric repetitions of knee flexion and were then given two minutes rest before completing the test trials. Following this, participants were instructed to perform three maximal concentric and eccentric knee flexion repetitions at an angular velocity of $60°s^{-1}$. The researcher conducted each test and provided standardised verbal encouragement during concentric ("pull") and eccentric ("push") actions. Gravitational correction factors of the isokinetic dynamometer's lever arm and the lower limb segment were calculated and applied automatically within the dynamometer measurements.

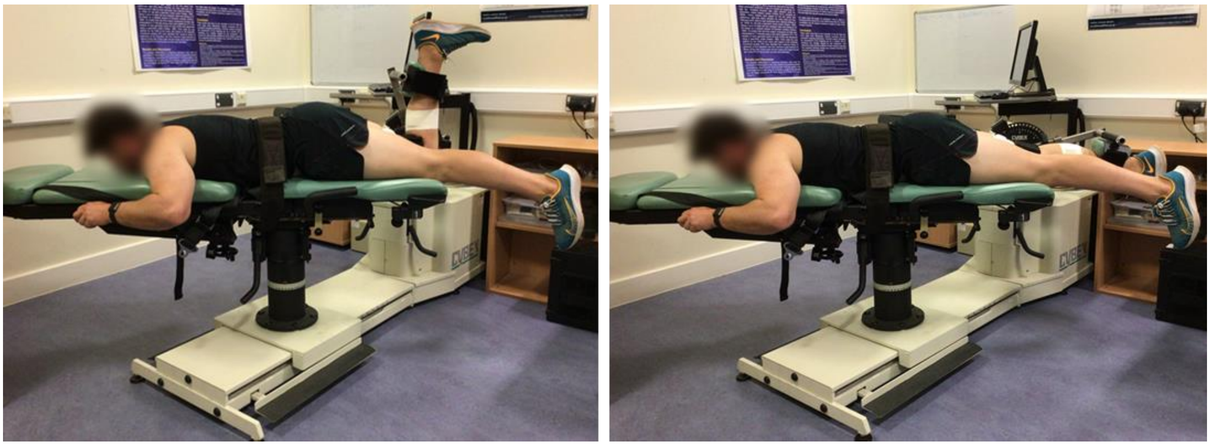

Figure 3.4 Single leg prone hamstring curl

b) Study 4

The double leg prone hamstring curl was completed on a Foreman - FN-103 lying leg curl machine. The participant lay prone on the machine with the hip in 10° flexion, the knees extended and the roller pad rested over the lower part of the calves. The exercise started with bilateral knee flexion, pulling the ankles as close to the buttocks as possible. The researcher verbally counted two seconds for the concentric knee flexion phase of the exercise and two seconds for the eccentric phase. The exercise was completed using loads of 20%, 35% and 50% of body weight.

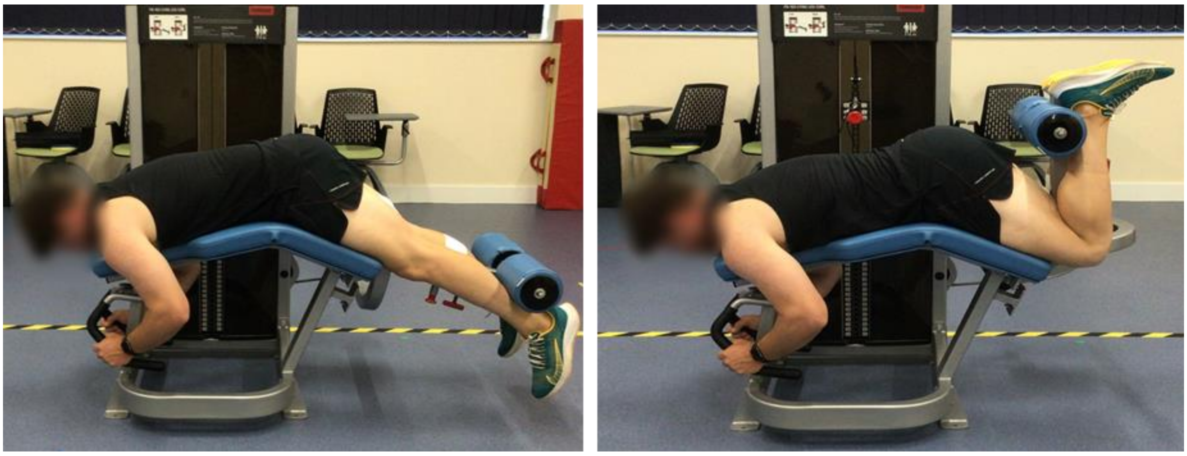

Figure 3.5 Double leg prone hamstring curl

4) Single leg bridge

This exercise was adopted from Freckleton and colleagues (2014). At the start of the exercise participants laid down in a supine position with one heel on a 60 cm high box. The ankle of the test leg was positioned in dorsiflexion and the knee positioned in 20° degrees of flexion which was measured with a goniometer. In study two, participants completed the exercise using body weight with their arms resting across their chest during each repetition, while in study four loads of 5%, 15% and 25% of body weight were used with participants being instructed to rest the bar across their lower abdomen while completing the exercise.

With their arms across their chest or holding a bar across their abdomen accordingly, participants posteriorly tilted their pelvis as they pushed down through the heel on the box to lift their bottom off the ground and extended their hips fully to zero degrees. From this position the hips were lowered, ensuring that the participants touched, but did not rest on the ground between repetitions. Full hip extension to zero and full return to the floor was required for each repetition or the test was stopped. Participants were encouraged to avoid any rotation of the limb during the exercise. The non-test leg was held in a fixed vertical position to make sure that momentum was not gained by swinging this leg. Each repetition took six seconds to complete and the researcher verbally counted two seconds for the upward movement, a two second isometric hold at the top of the bridge and two seconds to return to the starting position.

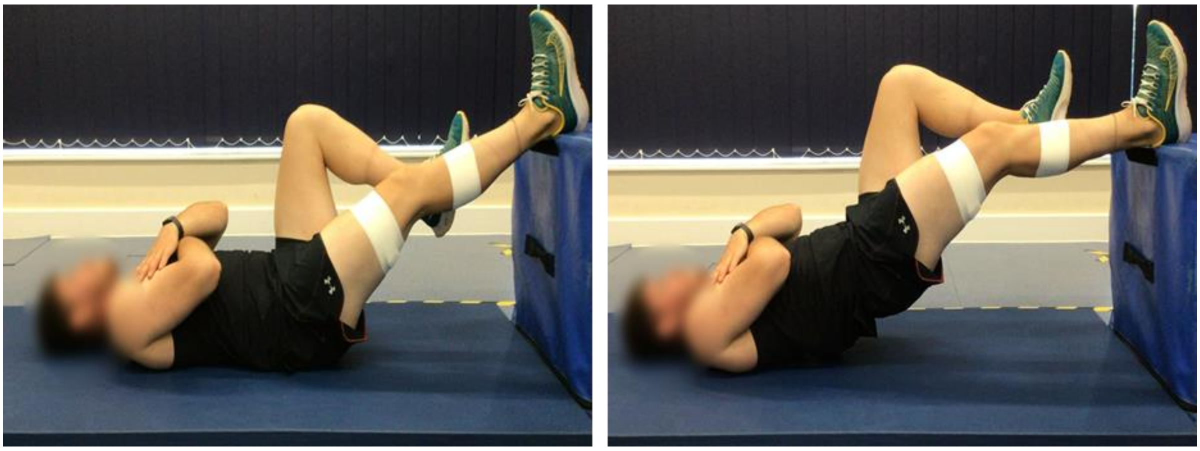

Figure 3.6 Single leg bridge with body weight

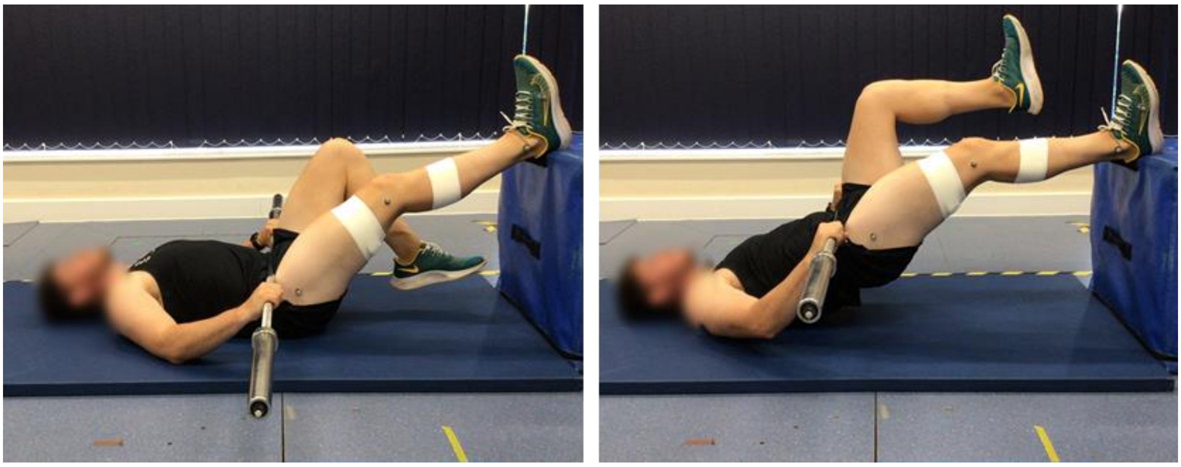

Figure 3.7 Single leg bridge with bar

5) Single leg Roman chair hold

This exercise was similar to that described by Van Hooren and Bosch (2017b). At the start of the exercise the participant was positioned facing down on the glute-hamstring raise bench with their hips over the thigh pad. The participant was positioned such that the anterior superior iliac spine was supported but the trunk remained unsupported. The hip joint was positioned in 20° flexion, the knee in 10° degrees flexion and the ankle hooked under the pad. The non-test leg rested above the support pad so that it did not provide any counterbalance. The participant was instructed to lift up, using a count of two seconds, as they raised their trunk parallel to the floor into a hip-lumbar neutral position. The trunk was held in position and then lowered back to the starting position using a count of two seconds. The researcher verbally counted the time during each repetition. In study two, the duration of trunk hold was two seconds and the participants completed the exercise using body weight and a 20kg bar, while in study four the trunk was held in position for a count of five seconds and loads of 10%, 20% and 30% of body weight were used.

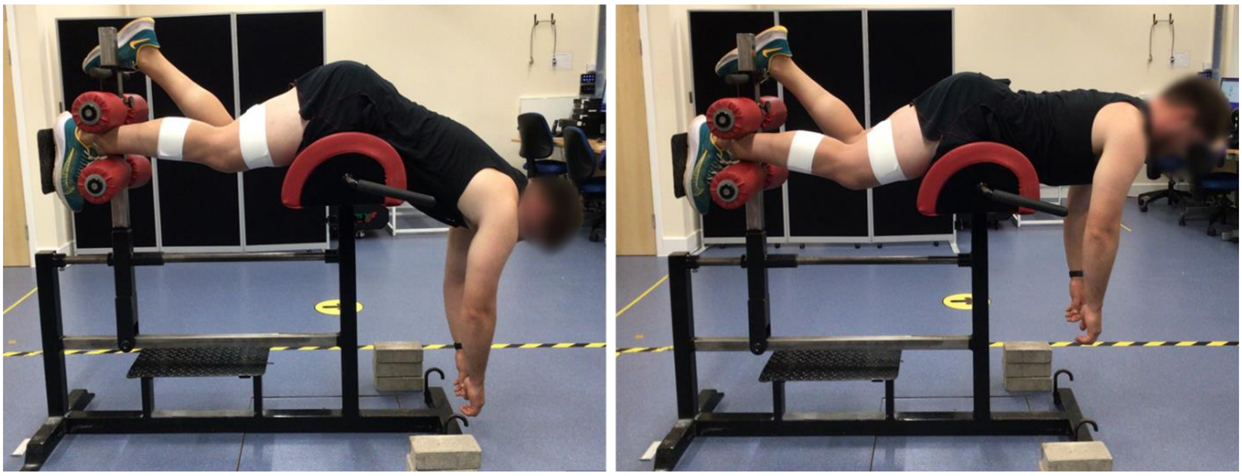

Figure 3.8 Single leg Roman chair hold with body weight

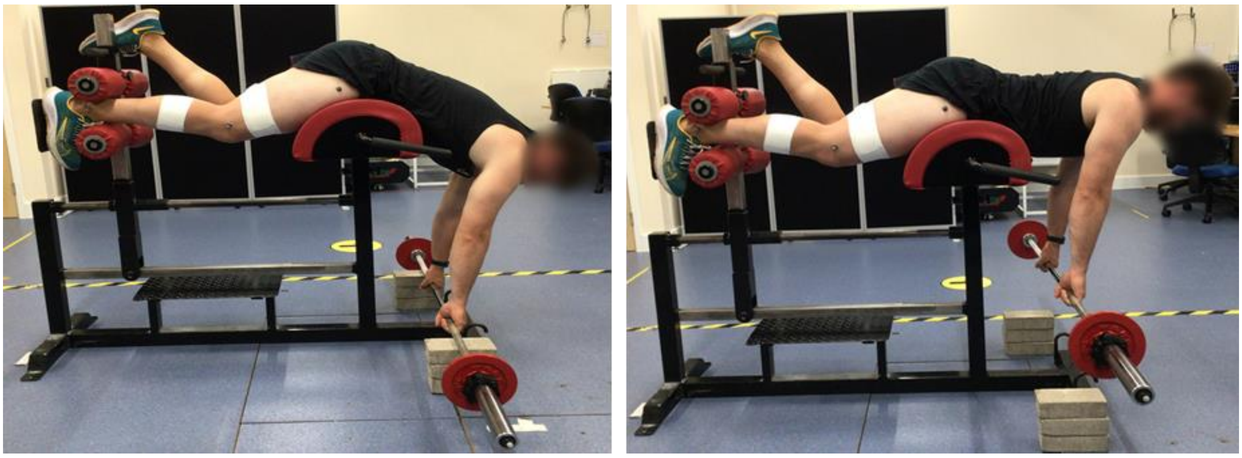

Figure 3.9 Single leg Roman chair hold with bar

3.2 Video analysis

a) Studies 1 and 2

One set of 20 sequentially illuminating light emitting diodes (LEDs) (Wee Beastie Electronics, Loughborough, UK), were used to synchronise the video data with sEMG data during the sprinting and exercise trials completed for studies one and two. The LEDs were triggered manually by remote control once they were in the view of the camera, and once activated a voltage drop was recorded within Vicon Nexus (v1.8.5, Vicon, Oxford Metrics, UK), which was being used to record sEMG data. The LEDs were placed in the field of view of the video camera and synchronisation was performed post-hoc to within 0.001s (Irwin and Kerwin, 2006). The video data was used to determine the start and end of each repetition of the exercises and to determine the phases of the sprinting gait cycle. This method was adopted because at the time of testing the VICON and sEMG measurement systems were not integrated and therefore two separate systems had to be used to synchronise the video and sEMG data.

b) Study 4

In study 4, the video camera was synchronised to the Vicon Nexus system and therefore sequentially illuminating LEDs were not required as the video data was collected through Vicon Nexus. Video data was used to determine the first stride completed by each participant in the maximal velocity phase (30 – 40 m) of the fastest sprinting trial while kinematic data was used to determine the start and end of each repetition of the exercises analysed (Boyer *et al.*, 2019). Details regarding the kinematic procedures are available later in this chapter.

3.3 Surface electromyography procedures

Surface electromyography was chosen as it is a more accessible and non-invasive method when compared to indwelling electrodes and is commonly used in research investigating muscle activation during different tasks and exercises (Besomi *et al.,* 2020; Prince *et al.,* 2021; van den Tillaar *et al.,* 2017; van Hooren *et al.,* 2022). The sEMG was used to measure the activity of up to five muscles of the lower limb using a portable sEMG system (Trigno Wireless EMG, Delsys, Boston, MA, USA; parallel bar configuration, inter-electrode distance 10mm, contact material 99.9% Ag, electrode size 37 x 26 x 15mm) with a sampling frequency of 2000Hz (Higashihara *et al.*, 2010a). The five lower limb muscles included were: BFlh, ST, GM, RF and MG. The BFlh was chosen as this is the most commonly injured hamstring muscle (Koulouris *et al.*, 2007). The ST forms a common conjoined tendon with the BFlh and neuromuscular co-ordination between the BF and ST muscles contributes to the vulnerability to HSI (Schuermans *et al.*, 2014) and secondary injury in ST is commonly observed (Askling *et al.*, 2007; De Smet and Best, 2000). The RF muscle was included due to its antagonistic role to the hamstrings during high-speed running. The GM muscle was included due to its role as a hip extensor and evidence suggesting that proximal muscle activity has a role to play in HSI risk and prevention (Sugiura *et al.*, 2008; Schuermans *et al.*, 2017), while a history of a previous calf injury has been reported to increase the risk of HSI (Green *et al.*, 2020) hence the inclusion of this muscle for analysis.

The electrode placement was determined by the use of the guidelines recommended by the sEMG for the Non-Invasive Assessment of Muscles project (SENIAM) (Hermens *et al.*, 2000).

For BFlh, the electrode was placed on the midpoint of the line between the ischial tuberosity and lateral tibial condyle. For ST, the electrode was placed on the midpoint of the line between the ischial tuberosity and medial condyle of the tibia. For GM, the electrode was placed at the midpoint of the line between the sacral vertebrae and the greater trochanter of the femur. For the MG, the electrode was placed on the most prominent part of the muscle. For RF, the electrode was placed at the midpoint of the line from the anterior superior iliac spine to the superior aspect of the patella.

All participants were asked to shave their dominant leg before arriving at the laboratory for testing. Prior to electrode placement the skin was prepared using an abrasive gel to remove any remaining hair in the area and the skin was cleaned with an alcohol wipe. The latter approach has previously been shown to reduce skin impedance to < 5kΏ (Robertson *et al.*, 2014). All electrodes were placed over the muscle belly and longitudinally with respect to the muscle fibre, with the location of each electrode outlined using a marker pen (Moore *et al.*, 2014), which served as a guide for the reattachment of the electrodes if they detached during testing. The electrodes were attached to the skin with double-sided tape and a self-adhesive tape was placed over each electrode to secure them in place and to minimize movement artifacts from the lower limb during the sprinting and exercise protocol (Albertus-Kajee *et al.*, 2011). To aid electrode placement palpation of each muscle belly during light isometric contraction was used and the quality of the sEMG signal was visually checked (Higashihara *et al.*, 2010a; Higashihara *et al.*, 2015a; Ono *et al.*, 2011).

3.4 Kinematic data

For the exercise trials in study four, non-invasive reflective markers were affixed to the tip of the acromion, greater trochanter of the femur, lateral femoral condyle of the femur, lateral malleolus of the fibula, lateral side of the calcaneus and the 5th metatarsophalangeal joint of the dominant arm and leg. One static calibration trial was recorded for each subject while they stood with their feet shoulder width apart and knees extended. This trial established local coordinate systems and all coordinate data was recorded using a data motion analysis system (Vicon, 200Hz) (Vicon Nexus, Oxford Metrix Inc, UK) and exported to Visual 3D (Visual 3D v6, C-Motion Inc, Germantown, USA) for further analysis.

3.5 Data analysis

The raw sEMG signal was imported into Visual 3D (Visual 3D v6, C-Motion Inc, Germantown, USA) where it was amplified and filtered. Residual analysis was used to determine the optimal high-pass and low-pass cut-off frequencies. A range of frequencies between 10-500 Hz were examined using residual analysis (Winter, 2009) and the optimum cut-off was determined as 10Hz (high-pass) and 175 Hz (low-pass). The sEMG signals were subsequently bandpass filtered (Butterworth zero-lag fourth-order filter) and then the data underwent full-wave rectification and smoothing using a moving root mean square window.

All data presented in the results and discussion chapters represent normalised values. The peak activity and iEMG of the first stride during the maximum velocity phase (30-40 m) of each participant's fastest sprinting trial was used for normalising the sEMG data recorded during the sprinting and exercises analysed. One stride cycle was determined as the point from ipsilateral foot contact to the following ipsilateral foot contact (Higashihara *et al.*, 2018). Peak activity was included to provide a measure of the maximal activity of the muscles analysed. Integrated EMG was chosen in addition to peak activity present information on the amount of muscle activation during sprinting and the exercises being analysed. There is no gold standard for normalising sEMG data however consideration needs to be given to the repeatability and validity of the method (Besomi *et al.,* 2020). Sprinting was chosen as the method of normalisation because using a dynamic activity has previously been shown to be more reliable than a maximal voluntary contraction (Albertus-Kajee *et al.*, 2011) and sEMG data has been reported to be more reliable when muscle activity is recorded during natural, unconstrained motion of the body (Suydam *et al.,* 2017). Furthermore, this method was considered more ecologically valid as the data is recorded at joint angles and muscle lengths that are comparable to the tasks under investigation (Burden, 2010) and sprinting is the most common mechanism of HSI (Huygaerts *et al.,* 2021; Kenneally-Dabrowski *et al.,* 2019b).

In addition to normalised peak (nEMG) and integrated muscle activity (niEMG), co-activation muscle ratios of nEMG peak activity and niEMG during the performance of each exercise were calculated for study 2 (Chapter 5). Co-activation ratios were calculated by dividing the normalised BFlh and ST peak and iEMG by the remaining muscles included in the study. Ratios > 1.0 indicated that either BFlh or ST were relatively more active than the other muscles respectively.

Chapter 4: Prelude

Chapter 2 presented literature identifying hamstring and synergistic muscle activation during sprinting. A biphasic pattern of hamstring activity occurs during sprinting, with activity being greatest during the early stance and late swing phases. The hamstrings contract eccentrically through late swing to decelerate the limb and control extension of the knee, while during the early stance phase a concentric contraction of the hamstrings occurs to extend the hip. Hamstring strain injury commonly occurs during early stance and late swing and thus knowledge of hamstring activation during these phases is relevant as it could contribute to exercise selection and hamstring training protocols. Existing literature regarding lower limb muscle activation during sprinting is largely based on data collected from sprinters and track and field athletes rather than team sports such as rugby union. Therefore, the first study of this thesis sought to analyse and compare lower limb muscle activity during the early stance and late swing phases of sprinting in rugby union players. However, it will need to be recognised that this work was only conducted using a very small sample of elite WRU players, and with no sEMG reliability data presented for the sample population.

Chapter 4

Lower limb muscle activity during maximal velocity sprinting

4.1 Introduction

Hamstring strain is the most common injury in running based sports and accounts for up to 16% of all injuries reported in athletes (Brooks *et al.*, 2006; Ekstrand *et al.*, 2011a; Orchard and Seward, 2002; Woods *et al.*, 2004), with the BFlh muscle being the most frequently injured muscle (Hallen and Ekstrand, 2014; Koulouris and Connell, 2003). Re-injury rates ranging between 22% and 34% have been recorded (Malliaropoulos *et al.*, 2011; Orchard and Seward, 2002), which are reported as being one of the highest recurrence rates for muscle injury (Ernlund and Vieira, 2017). In many cases, HSIs result in a prolonged absence from training and competition, which subsequently has significant financial implications for clubs (Brooks *et al.*, 2006; Hickey *et al.*, 2014) and a negative effect on performance (Opar *et al.*, 2012). Specifically, the mean number of days lost due to HSI is influenced by the severity and location of injury and ranges from eight (Feeley *et al.*, 2008) to 26 days (Brooks *et al.*, 2006). Sprinting is described as a common cause of HSI however, the mechanism is not fully understood. Consequently, the development of injury prevention programmes is difficult (Hansen *et al.*, 2017) and may explain why the incidence of HSI has not reduced in the past few decades (Ekstrand *et al.*, 2016).

Hamstring function is a fundamental part of running as the muscles control the forces around the hip and knee joints (Schuermans *et al.*, 2017c). The hamstring muscle group work to decelerate the extending limb during the late swing phase of running, while during stance the hamstrings extend the hip and work to stabilise the knee joint and contribute to the production of propulsive ground reaction forces (Hansen *et al.*, 2017; Howard *et al.*, 2018). An understanding of hamstring muscle activity during sprinting and recognising when the muscles are most susceptible to injury is important as it could contribute to the development of exercises to optimise hamstring activation.

Hamstring activity is at its highest during the early stance and late swing phases of sprinting (Higashihara *et al.*, 2015a; Yu *et al.*, 2008) and activation increases with running speed (Hegyi *et al.*, 2019b; Higashihara *et al.*, 2010a Schache *et al.*, 2013), with a greater risk of HSI being proposed as a consequence (Higashihara *et al.*, 2010a; Schache *et al.*, 2012). There is no consensus concerning the point at which hamstring injuries happen during sprinting. Some authors suggest that injury occurs during late swing when muscle activity is at its highest and the MTU's are working at their longest length (Chumanov *et al.*, 2012; Schache *et al.*, 2012; 2013; Yu *et al.*, 2008); while others describe the early stance phase (Opar *et al.*, 2015; Orchard, 2012) where muscle activation is also high and the hip extension and knee flexion torques are at their maximum (Mann, 1981). More recently however the swing-stance transition has been proposed as the period where HSI risk is at its greatest, rather than in either phase in isolation (Liu *et al.*, 2017).

In an attempt to identify factors that contribute to the vulnerability of the hamstrings to injury, the activation of lower limb muscles in addition to the hamstrings appears warranted. In conjunction with the hamstrings, the GM muscle acts to extend the hip and its role as a synergist in the posterior chain is significant as a means of minimising hamstring overload and injury (Schuermans *et al.*, 2017a). Furthermore, GM weakness is associated with increased HSI risk (Sugiura *et al.*, 2008). The risk of HSI is reported to increase by up to 50% if individuals report a previous history of calf injury (Green *et al.*, 2020; Orchard, 2001), thus signifying the investigation of gastrocnemius during sprinting as a means of contributing to hamstring training programmes. A recent study by Bramah and colleagues (2021) reports that runners with a history of calf muscle injury demonstrated increased contralateral anterior pelvic tilt and pelvic drop, which the authors inferred may be due to deficits in gluteal muscle activation. Collectively, it appears that altered gluteal muscle activation may negatively influence both hamstring and calf muscle injury risk. Finally, as the hamstrings are reported to work eccentrically during the swing phase of running to decelerate the lower limb (Yu *et al.*, 2008), examining the antagonistic activation of the quadriceps may identify any evidence of quadriceps dominance, the consequence of which requires the hamstrings to work harder to counter the force produced by the quadriceps (Best and Tietze, 2014).

While it is not possible to definitively conclude when HSI occurs during sprinting, the early stance and late swing phases appear to be the most clinically relevant as these phases are when hamstring injury risk is at its greatest (Liu *et al.*, 2017; Orchard, 2012). Furthermore, hamstring muscle demands differ between the acceleration and maximal velocity phase of sprinting (Higashihara *et al.*, 2018) and as hamstring activation and load increase as a consequence of increasing speed (Chumanov *et al.*, 2011), it appears reasonable to suggest that the maximal velocity phase may present a greater risk of HSI risk compared to the acceleration phase.

Analysing the activity of additional lower limb muscles rather than the hamstrings in isolation, will provide evidence of muscle activation and may provide insight with regards to muscle loading during sprinting which can contribute to, and facilitate the development of training programmes to optimise hamstring activation. Therefore, the aim of this study was to analyse and compare lower limb muscle activity during the early stance and late swing phase of the maximum velocity phase of sprinting.

4.2 Methods

4.2.1 Experimental procedures

Ten male rugby union players (mean ± SD: age = 22.9 ± 2.9 years; height = 1.83 ± 0.54 m; mass = 94.5 ± 9.6 kg) from an international sevens team were recruited for the study. Players had to meet the following inclusion criteria: 1) have no history of lower limb injury that has caused more than five days absence from training or matches in the last six months; 2) have no history of lower limb surgery; 3) be aged between 18-30 years old; 4) be injury free and healthy at the time of data collection and 5) be selected for an international sevens team at the time of testing. This study was approved by the Cardiff School of Sport and Health Sciences Ethics committee (Appendix 1) and all participants were given an information sheet (Appendix 2) and provided written informed consent prior to data collection (Appendix 3). All participants completed 3 x 40 m sprint trials and sEMG was used to quantify lower limb muscle activity of the right leg during all trials. For specific details regarding the sEMG procedures, sprinting protocol and data analysis see chapter 3.

4.2.2 Data collection

All participants wore their own trainers, socks, shorts and vests during data collection. Each participant completed the same testing protocol which included a 20-minute warm-up, the placement of sEMG electrodes and 3 x 40 m sprints. The activity of BFlh, ST, RF, GM and MG was recorded using a portable sEMG system as per the description in chapter 3. The right leg was chosen for analysis regardless of limb dominance (Higashihara *et al.*, 2015a; Nummela *et* *al.*, 1994; Ono *et al.*, 2015) as lower limb dominance has no significant effect on HSI in rugby (Brooks *et al.*, 2006; Fuller *et al.*, 2011).

4.2.3 Surface electromyography normalisation procedures

The data for the three sprint trials was normalised to the highest peak and iEMG respectively (Renshaw *et al.*, 2010), which occurred during the first stride in the maximal velocity phase (30 – 40 m) of each participant's fastest running trial. After the data was normalised the mean value across the three sprint trials was then calculated and the normalised sEMG signal was quantified via two methods: peak muscle activity and iEMG. All data presented in the results and discussion therefore represent normalised values.

4.2.4 Sprint protocol

Participants completed 3 x 40 m sprint trials and five minutes rest was provided in between each trial to minimise the effects of fatigue (van den Tillaar *et al.*, 2017). All sprint trials took place on an indoor synthetic running track (Mondo, Warwickshire, UK) in the NIAC at the School of Sport and Health Sciences, Cardiff Metropolitan University. Details regarding the sprint protocol and data collection can be found in chapter 3.

4.2.5 Statistical analyses

The sEMG data was analysed using SPSS 24.0 software. A Shapiro-Wilk test showed that the majority of the data was normally distributed and subsequently a two-way analysis of variance (ANOVA) with repeated measures (5 x 2; muscle [BFlh; ST; RF; GM; MG] x sprinting phase [EST; early stance phase and LSW; late swing phase]) was used to compare the means between the participants that were divided based on two within-subjects factors (O'Donoghue, 2012). The level of statistical significance was set at $p \leq 0.05$. If sphericity was violated according to Mauchly's test, then the Greenhouse-Geisser adjustment was applied and if a non-significant result was obtained from this adjustment, then the Huynh-Feltd correction was used. If the ANOVA showed significant interactions or main effects then Bonferroni's *post hoc* analysis was used (Higashihara *et al.*, 2015; van den Tillaar *et al.*, 2017). The interactions between sprint phase and muscle were the most relevant part of the data analysis as the aim of the study was to determine muscle activity during phases of the running gait cycle.

Results are presented as means ± standard deviations (SD) and partial eta squared was used to assess the effect sizes, using $0.01 < \eta^2 < 0.06$ as a small effect, $0.06 < \eta^2 < 0.14$ as a medium effect and $> 0.14\ \eta^2$ as a large effect (van den Tillaar *et al.*, 2017). Irrespective of significance, the magnitude of difference between variables for the pairwise comparisons were determined via Cohen's *d* effect size statistics, as the study aimed to understand which phase of sprinting activated each muscle to the greatest degree. The criteria used were trivial ($d \leq 0.2$), small ($d \leq$ 0.2-0.49), medium ($d \leq$ 0.5-0.79) and large ($d \geq 0.80$) effect sizes (Cohen, 1992).

4.3 Results

Due to some technical difficulties resulting in only some of the required data being collected for some participants and electrode movement generating incomplete sEMG traces, it was only possible to analyse data from five participants. The mean sprinting speed over 40 m was 8.0 ± 0.28 and participants achieved maximal running velocity between 30 – 40 m. The results which follow are based on the sEMG data recorded in this window of the sprint trials.

4.3.1 Mean muscle activity

The mean activity for all muscles analysed before and after the normalisation process is presented in figure 4.1 and 4.2. Muscle activation was highest during the early stance and late swing phase for all muscles analysed. As per the aims of the study, the data are subsequently analysed for the early stance and late swing phases.

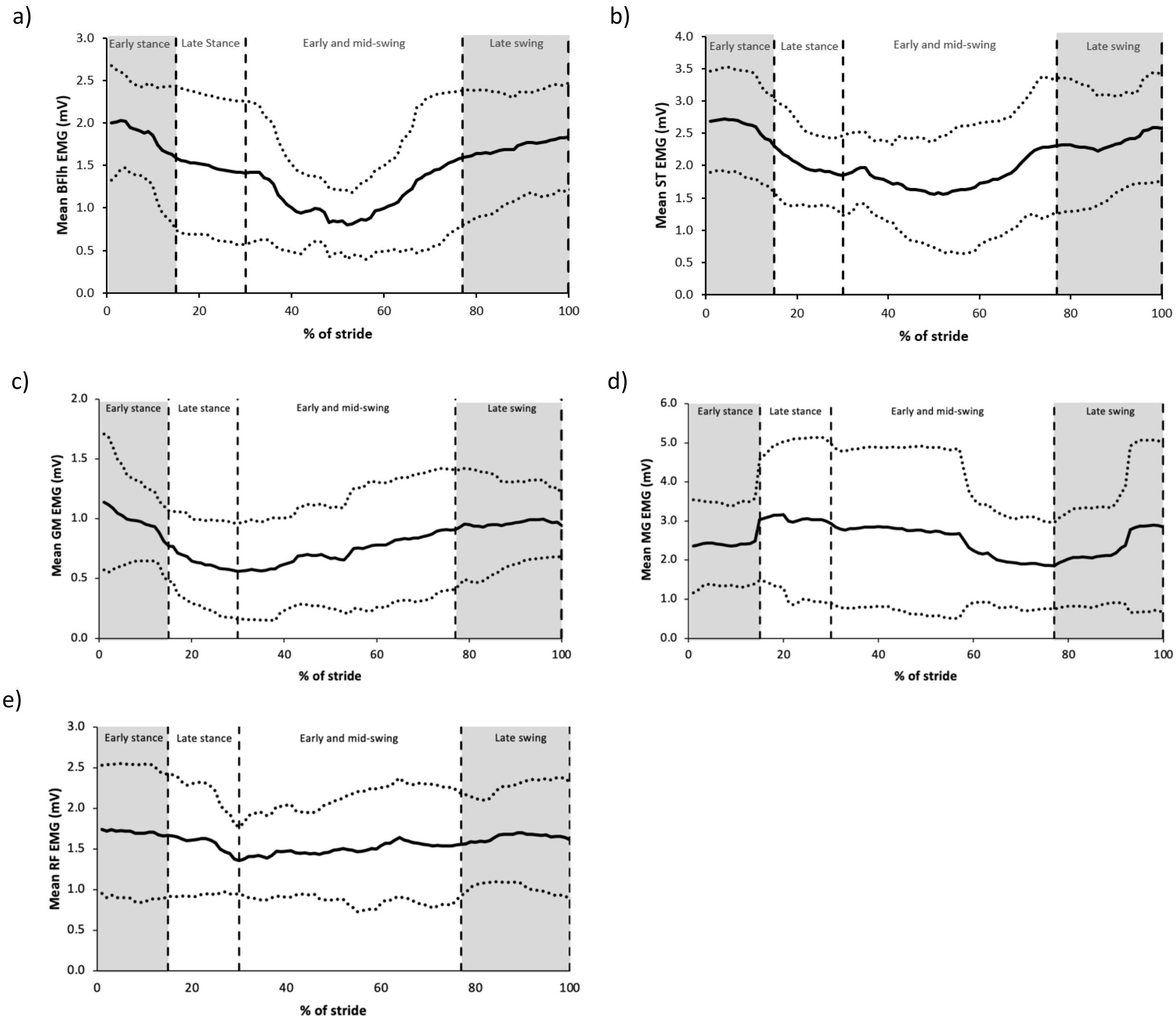

Figure 4.1 Muscle activity (mV) during sprinting. The black line represents mean activity and the dotted lines mean activity +/- the standard deviation. a = biceps femoris long head (BFlh); b = semitendinosus (ST); c = gluteus maximus (GM); d = medial gastrocnemius (MG); e = rectus femoris (RF)

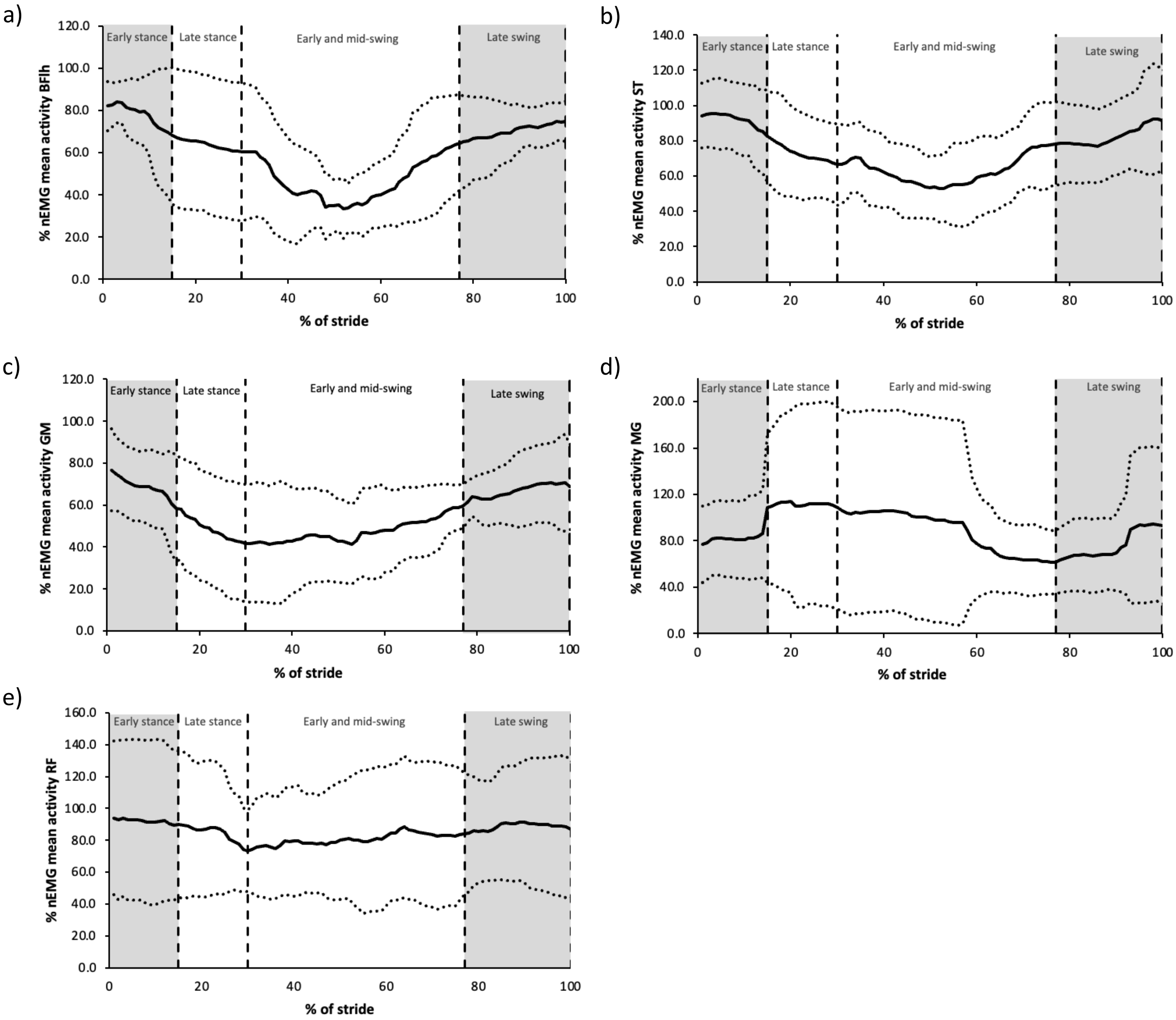

Figure 4.2 Normalised muscle activity during sprinting. The black line represents mean activity and the dotted lines mean activity +/- the standard deviation. a = biceps femoris long head (BFlh); b = semitendinosus (ST); c = gluteus maximus (GM); d = medial gastrocnemius (MG); e = rectus femoris (RF)

Table 4.1 Normalised (%) peak activation (mean ± SD) for lower limb muscles during the early stance and late swing phases of maximal velocity sprinting.

Sprint phase	BF peak nEMG	ST peak nEMG	RF peak nEMG	MG peak nEMG	GM peak nEMG
EST	89 ± 15	80 ± 16	83 ± 27	132 ± 81	82 ± 16
LSW	89 ± 10	85 ± 13	83 ± 17	130 ± 80	82 ± 18

Key: Early stance phase (EST); Late stance phase (LST)

4.3.2 Normalised peak muscle activity

The normalised values (nEMG) for peak activity during early stance and late swing are presented in table 4.1 and figure 4.3. For peak activity there was no significant interaction effect for sprint phase and muscle ($F_{1,4}$ = 0.11, p = 0.978, η^2 = 0.026) and there was no significant main effect for sprint phase ($F_{1,4}$ = 0.08, p = 0.787, η^2 = 0.020) or muscle ($F_{4,16}$ = 1.47, p = 0.258, η^2 = 0.269). While no significant findings were observed for peak activity, MG activation was higher than all other muscles during both phases of sprinting. Observation of the data showed that two of the participants had very high MG peak values in comparison to the remainder of the group and this is demonstrated by the large SD for the MG data (Table 4.1). For the BFlh, GM and RF, the peak activity generated by the individual muscles reached the same amplitude in early stance and late swing, while ST reached peak activity during the late swing phase (Table 4.1).

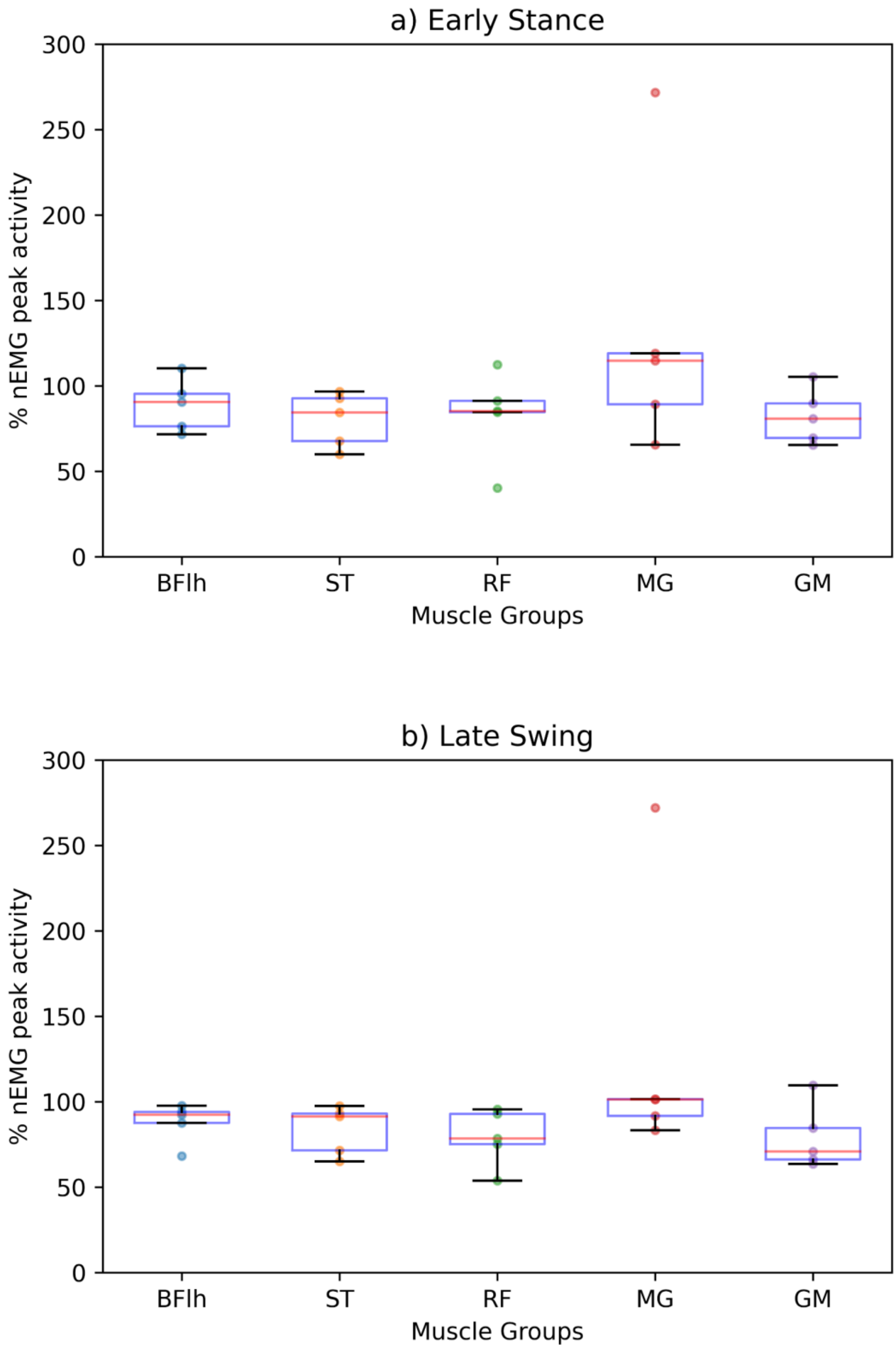

Figure 4.3 Box and whisker plots, figures a and b show the minimum value, 1st quartile, median value, 3rd quartile, maximum value and outliers of normalised peak muscle activation (% nEMG) of biceps femoris long head (BFlh); semitendinosus (ST); gluteus maximus (GM); medial gastrocnemius (MG) and rectus femoris (RF) during a) early stance (EST) and b) late swing (LSW) phases of maximal velocity sprinting.

4.3.3 Within sprint phase differences

Cohen's *d* calculations were computed for the peak nEMG data for the early stance and late swing phases. Biceps femoris long head activity was higher relative to ST, GM and RF across the early stance and late swing phases of the stride. There was a large mean difference in peak hamstring activity in early stance (*d* = 1.91) and a small mean difference (*d* = 0.37) between hamstring activity in the late swing phase. Gluteus maximus activity showed a medium and trivial mean difference between the BFlh (*d* = 0.59) and ST (*d* = 0.13) muscles respectively in the early stance phase, while a small and trivial mean difference were observed between GM and hamstring peak activity respectively (BFlh *d* = 0.41; ST *d* = 0.15) during late swing. Medial gastrocnemius activity was higher than the hamstrings during the stride, with a small mean difference between MG and BFlh (*d* = 0.47) during early stance and a medium mean difference (*d* = 0.53) between the two muscles during the late swing phase. The higher MG peak activity compared to the ST muscle revealed a medium mean difference for both the early stance (*d* = 0.57) and late swing phases (*d* = 0.52). A trivial mean difference was observed between hamstring and RF activity during early stance, while for the late swing phase a small and trivial mean difference was evident between RF and BFlh (*d* = 0.33) and RF and ST (*d* = 0.10) respectively.

Table 4.2 Normalised (%) iEMG (mean ± SD) of lower limb muscles during the early stance and late swing phases of maximal velocity sprinting.

Sprint phase	BF niEMG	ST niEMG	RF niEMG	MG niEMG	GM niEMG
EST	18 ± 4	19 ± 5	19 ± 8	22 ± 12	19 ± 3
LSW*	31 ± 8	28 ± 7	25 ± 4	30 ± 15	31 ± 9

Key: Early stance phase (EST); Late swing phase (LSW). * Significantly higher niEMG for all muscles compared to the early stance phase.

4.3.4 Normalised integrated EMG

Normalised iEMG during early stance and late swing are presented in figure 4.3. There was no significant interaction effect for sprint phase and muscle ($F_{4,16}$ = 7.35, p = 0.582, η^2 = 0.155) and niEMG did not show a significant main effect for muscle ($F_{4,16}$ = 0.315, p = 0.864, η^2 = 0.073). A significant main effect was observed for sprint phase ($F_{1,4}$ = 20.434, $p \leq 0.011$, η^2 = 0.836), with higher mean activity occurring during the late swing phase.

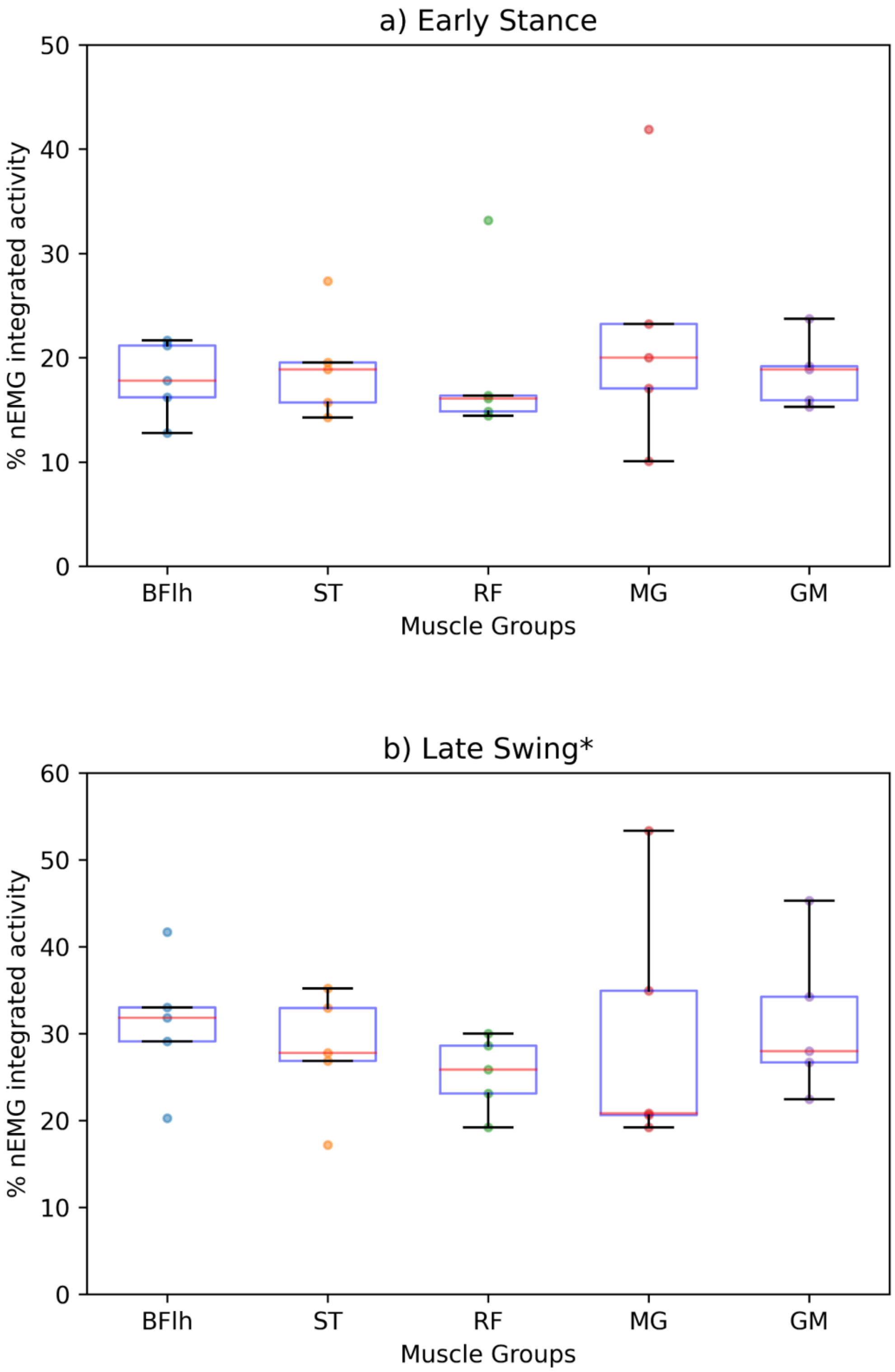

Figure 4.4 Box and whisker plots, figures a and b show the the minimum value, 1st quartile, median value, 3rd quartile, maximum value and outliers of normalised integrated EMG (% niEMG) of biceps femoris long head (BFlh); semitendinosus (ST); gluteus maximus (GM); medial gastrocnemius (MG) and rectus femoris (RF) during a) early stance (EST) and b) late swing (LSW) phases of maximal velocity sprinting. * Significantly higher niEMG for all muscles compared to the early stance phase.

4.3.5 Within sprint phase and muscle differences

Significantly higher muscle activation occurred in the late swing phase compared to early stance (Table 4.2 and Figure 4.4). Cohen's *d* calculations were computed for the niEMG data for the early stance and late swing phases and muscles. The niEMG of the BFlh and GM muscles during the early stance and late swing phases demonstrated a large mean difference (BFlh *d* = 1.88; GM *d* = 2.08) while a medium mean difference was observed for the ST (*d* = 0.78), RF (*d* = 0.54) and MG muscles (*d* = 0.56) during the two phases.

During the early stance phase, there was a trivial mean difference between hamstring activity (BFlh vs. ST *d* = 0.16) and a trivial difference between hamstring and RF activity (BFlh vs. RF *d* = 0.16; ST vs. RF *d* = 0.02) and GM activity (BFlh vs. GM *d* = 0.16; ST vs GM *d* = 0.08), while a small mean difference was observed between MG and hamstring activity (BFlh vs. MG *d* = 0.41; ST vs. MG *d* = 0.21) with MG niEMG being higher. During the late swing phase, BFlh niEMG was higher than the ST muscle and a large mean difference (*d* = 0.99) between the niEMG of these muscles was observed. A trivial mean difference was observed between hamstring and MG activity (BFlh vs MG *d* = 0.17; ST vs MG *d* = 0.14) and BFlh and GM activity (BFlh vs. GM d = 0.02), while a small mean difference was evident for ST and GM (*d* = 0.38) with higher GM activity relative to ST being observed. The hamstring niEMG was higher than the RF muscle with large (BFlh vs. RF *d* = 0.86) and small (ST vs. RF *d* = 0.36) mean differences being observed respectively during late swing.

4.4 Study limitations

Due to some technical difficulties the final sample size was five. While this resulted in a small sample size, other studies have used similar participant numbers (Ono *et al.*, 2010; Schache *et al.*, 2013). The ability to detect significance will have been influenced by both sample size and the number of comparisons. An increase in Type II error may have occurred due to the relatively small sample size and therefore the findings obtained are likely to have been more descriptive of the population investigated if a larger sample size had been available. However, effect sizes were also used in addition to significance testing and these revealed meaningful differences in muscle activation patterns. No measurement of sEMG reliability was completed as part of the current study and this should also be considered when interpreting the findings.

Muscle activation has been suggested to be influenced by training history and experience (van den Tillaar *et al.*, 2017). While the participants recruited for the current study were from the same rugby team and had a similar training background, individual participant muscle strength may differ which may have influenced the sEMG data recorded. Furthermore, the positional demands of each player and individual muscle recruitment strategies may contribute to the findings observed. Collectively, these may explain the inter-participant variability observed for the MG muscle in particular. The number of strides completed in the 30 – 40 m window analysed varied across participants with some completing one stride and others two, and therefore to ensure consistency, the highest muscle activation in the first stride was used for the sEMG normalisation process. However, this approach may have influenced the normalised data outputs as the highest activation may have occurred in the second stride for those participants who demonstrated more than one stride.

The right leg was used for all participants regardless of limb dominance which is a method that has been adopted previously (Higashihara *et al.*, 2015a; Nummela *et al.*, 1994). Limb dominance has been reported to have no effect on hamstring injury incidence in running based sports (Freckleton and Pizarri, 2013; Orchard, 2001) however this methodological approach may underestimate or overestimate the muscle activity recorded. The definition of limb dominance also requires consideration as there is some debate to how it is defined with some using the kicking leg (Hegyi *et al.*, 2019b; Pinniger *et al.*, 2000) and jumping leg (Kobayashi *et al.*, 2013). Furthermore, limb dominance may be associated with a specific task or skill (McGrath *et al.*, 2016) and therefore relates to the context of a situation thus making it more challenging to assess and agree a definition.

4.5 Discussion

The aim of the study was to analyse and compare lower limb muscle activity during the early stance and late swing phases of the maximum velocity phase of sprinting. There were no significant interactions or main effects for peak muscle activity for sprint phase and muscle, while a statistically significant main effect ($p \leq 0.001$) for niEMG was observed for sprint phase only with significantly more activity during the late swing phase compared to early stance, and this was associated with a large effect size ($\eta^2 \geq 0.14$).

4.5.1 Biceps femoris long head and Semitendinosus activation

The study demonstrated that the BFlh muscle had the same degree of peak activity during the early stance and late swing phases, while the highest peak activity for ST occurred during the late swing phase. These findings support previous sEMG studies that report a biphasic BFlh and ST activity pattern with the highest activation occurring in the late swing and early stance phases of sprinting (Hegyi *et al.*, 2019b; Higashihara *et al.*, 2015a; Schache *et al.*, 2013). Biceps femoris long head has been shown to be selectively recruited as a strong hip extensor during the early stance phase of sprinting (Higashihara *et al.*, 2015a) and the higher BFlh peak activity and large mean difference observed when compared to the ST muscle in the current study appears to support this. Furthermore, hamstring niEMG was similar during early stance while the mean peak activity for the BFlh muscle was greater than ST during this phase. This may suggest that the BFlh is doing relatively more work than the ST muscle which might increase the muscle's susceptibility to injury. Collectively, based on the findings of this study, it could be argued that increasing ST peak activation during the early stance phase to encourage a more balanced within hamstring activation may afford protective benefits to the BFlh muscle.

The current study demonstrates that hamstring niEMG was higher during late swing when compared to early stance; a finding that was statistically significant and mirrors previous work showing that the hamstrings are most highly activated during the late swing phase (Chumanov *et al.*, 2011; Thelen *et al.*, 2005b). The latter may be reflective of a pre-activation of the hamstrings as their role in late swing is to control knee extension and decelerate the forward swing of the leg in preparation for ground contact (Kyrolainen *et al.*, 2005; Sugiura *et al.*, 2008). The marginally longer duration of the late swing phase (23% of the gait cycle) compared to early stance (15% of the gait cycle) (Howard *et al.,* 2018) will also influence the higher niEMG and the longer period of sustained muscle activation observed. Hamstring load is at its greatest during the swing phase of sprinting (Schache *et al.*, 2010), as the muscles experience peak force (Schache *et al.*, 2010) and musculotendon stretch, which is comparable to mechanical strain (Chumanov *et al.*, 2007), while contracting eccentrically (Chumanov *et al.*, 2011, Schache *et al.*, 2012). Additionally, an increase in running speed increases peak force and load during late swing, while force is independent of speed during the stance phase

(Chumanov *et al.*, 2011). As a result, the high level of hamstring niEMG combined with high mechanical load likely contributes to the hamstring vulnerability during the late swing phase when compared to early stance.

4.5.2 Gluteus maximus activation

In the current study, the same degree of peak GM activity was generated during the early stance and late swing phases; a pattern which mirrors the findings observed for BFlh peak activation. This finding is supported by previous work demonstrating peak GM activity during the early stance (Bartlett *et al.*, 2014; Jonhagen *et al.*, 1996; Kyrolainen *et al.*, 2005; Mero and Komi, 1987) and late swing phase of sprinting (Jonhagen *et al.*, 1996; Kyrolainen *et al.*, 2005). During sprinting, hip extension moments are greater than the flexion moments at the knee (Higashihara *et al.*, 2018) and evidence suggests that decreased GM activity can influence hamstring load and injury risk (Chumanov *et al.*, 2007; Nagano *et al.*, 2014; Schuermans *et al.*, 2017a; Sugiura *et al.*, 2008).

In the current study BFlh peak activity was higher relative to GM in early stance with a medium mean difference being observed, while ST and GM activity was very similar demonstrating a trivial difference. During the late swing phase, both BFlh and ST demonstrated a higher peak activation relative to GM yet there was only a trivial difference between ST and GM peak activity while a small mean difference was observed between BFlh and GM. Conversely, there was only a trivial difference between the niEMG of BFlh and GM during the late swing phase while ST activation was lower relative to the GM muscle with a small mean difference. These findings may imply that the GM muscle generates a more constant pattern of activation as evidenced by the niEMG, compared to BFlh which produced higher peak activity and a greater magnitude of difference in the late swing and early stance phases. In light of these findings and acknowledging the influence of GM activation on hamstring injury risk, knowledge of hip extensor muscle activity during training exercises would be worthwhile as the hamstrings and GM may generate different activation patterns which may influence exercise selection and prescription.

4.5.3 Medial gastrocnemius activation

Both phases of the stride generated a high level of MG peak activity (Table 4.1 and 4.2); similar findings have been reported previously (Jonhagen *et al.*, 1996). Medial gastrocnemius peak activity was higher relative to both hamstring muscles during the stride. The eccentric contraction of the plantar flexors at ground contact to break the negative vertical velocity that occurs (Mann and Sprague, 1980) suggests that a high peak MG would be expected during the early stance phase. However, the large SD observed requires consideration when interpreting the findings (Table 4.1 and 4.2) as this indicates a large variation in MG activation among participants.

The late swing phase generated significantly higher MG niEMG when compared to early stance (Table 4.2 and Figure 4.4) which may be a consequence of the longer duration of the late swing phase which represents the final 23% of the stride when compared to early stance which accounts for the first 15% of the stride (Howard *et al.*, 2018). In comparison to early stance, only a trivial difference between MG and hamstring niEMG was observed during the late swing phase, indicating a more relatively balanced, constant degree of knee flexor activation. As the hamstrings experience the greatest load during the swing phase (Schache *et al.*, 2010), it appears reasonable to suggest that finding of similar MG and hamstring activity in late swing is a positive finding. Furthermore, the co-contraction of the knee flexors would serve to prepare the limb for the load experienced at ground contact. While discussion of the MG activation patterns in the current study are somewhat limited due to the large variation observed in the data, a previous history of calf injury is an established risk factor for hamstring injury (Green *et al.*, 2020; Orchard, 2001), and therefore consideration of the gastrocnemius muscle in hamstring injury prevention programmes appears justified.

4.5.4 Rectus femoris activation

Peak RF activity has previously been reported during the early stance phase of maximal sprinting (Mero and Komi, 1987; Montgomery *et al.*, 1994) and similar findings were observed in the current study. The late swing phase generated the same degree of RF peak activity as that observed during the early stance phase, which mirrors the pattern of BFlh and GM peak activity. This pattern of RF activity was expected as maximum hip flexion occurs in the late swing phase and continues until the foot touches the ground (Mann and Sprague, 1980) with the muscle subsequently attenuating the force experienced at foot contact during sprinting (Nummela *et al.*, 1994).

The current study demonstrated somewhat similar hamstring versus RF activity, particularly when comparing ST and RF activity. Biceps femoris long head niEMG was, however, higher relative to RF in the late swing phase with a large mean difference being observed compared to the trivial difference in activation during early stance. The quadriceps provide the force for knee extension in the late swing phase and the hamstrings contract to produce force to counteract the action and absorb the energy developed by the knee extensors (Dolman *et al.*, 2014; Garrett *et al.*, 1987). The higher magnitude of BFlh activation relative to RF in the current study implies that the lateral hamstring played a more dominant antagonistic role when compared to the ST muscle as knee extension occurred in the late swing phase. This finding suggests the importance of RF training to support the hamstrings during sprinting as a means of encouraging a balanced degree of agonist and antagonist activation.

4.6 Conclusion

The current study used sEMG to determine the lower limb muscle activation patterns during the early stance and late swing phases of sprinting. The findings show that BFlh demonstrated relatively higher activation compared to the ST, GM and RF muscles. The late swing phase generated significantly higher niEMG across all muscles compared to early stance. The latter, in conjunction with the high peak activity generated in late swing, portrays the higher muscular demands of the late swing phase, and adds to existing evidence which identifies the late swing phase of sprinting as the period when the hamstrings are potentially most vulnerable to injury. Collectively, the results of the current study infer that increasing the activity of ST may be of benefit as a means of providing more support to the BFlh muscle which is the most commonly injured hamstring muscle. Furthermore, GM and MG activation needs to be taken in to account to target the synergistic hip extensor and knee flexor role of the muscles respectively as a means of encouraging balanced activation of the posterior chain during sprinting.

Chapter 5: Prelude

Chapter 4 provided data which examined lower limb muscle activation during sprinting and identified that hamstring activity was at its highest during the early stance and late swing phases, thus confirming the biphasic pattern of hamstring activity which has previously been reported. As sprinting is the most common cause of HSI, information regarding patterns of muscle activity could serve to inform injury prevention protocols. Research has identified that training exercises can result in divergent hamstring activity, therefore chapter 5 sought to further examine lower limb muscle activity during different hamstring strength training exercises. Identifying exercises that generate higher hamstring activation relative to that observed during sprinting could serve to optimise the activity of the hamstring muscles and contribute to the mitigation of injury risk. It needs to be recognised that this work was completed using a very small sample of elite WRU players, and no reliability data are presented for the sEMG collected for this sample population.

Chapter 5

Lower limb muscle activity during hamstring strength training exercises

5.1 Introduction

Hamstring strain injuries are common in sports which involve high-speed running and sprinting (Brooks *et al.*, 2006; Ekstrand *et al.*, 2011; Orchard and Seward, 2002; Woods *et al.*, 2004) and have a relatively high re-injury rate (Malliaropoulos *et al.*, 2011; Orchard and Seward, 2002). Due to the susceptibility for injury and re-injury, the hamstring muscle group is of specific interest as injuries can result in a substantial amount of time out of play (Wan *et al.*, 2017a; Wan *et al.*, 2017b) and create a considerable financial burden on teams (Hickey *et al.*, 2014). In addition, recurring injuries have been found to result in more time lost from sport when compared to initial HSIs (Brooks *et al.*, 2006). Therefore, preventing both initial and recurrent HSI is important for running based sports.

Injury is multi-factorial in nature and identified risk factors for HSI include muscle weakness (Timmins *et al.*, 2016a), reduced hamstring strength-endurance (Schuermans *et al.*, 2016) decreased optimum muscle length (Brockett *et al.*, 2004; Timmins *et al.*, 2016a), altered neuromuscular control (Schuermans *et al.*, 2014) and previous HSI (Koulouris *et al.*, 2007). Addressing modifiable risk factors for injury is possible via exercise selection. In particular the literature advocates eccentric exercise to increase hamstring muscle strength (MjØlsnes *et al.*, 2004; Schmitt *et al.*, 2012; Tyler *et al.*, 2014) and optimum muscle length (Brockett *et al.*, 2001). Encouraging results have been shown when using such an approach, including reduced HSI incidence with a NHE intervention (Arnason *et al.*, 2008; Van der Horst *et al.*, 2015), a decrease in the number of recurring HSI after return to sport (Tyler *et al.*, 2014), and earlier return to sport after injury (Askling *et al.*, 2013; Askling *et al.*, 2014) following interventions using other lengthening exercises.

Eccentric exercises train the hamstrings in a lengthened position which mimics the elongated muscle lengths observed during the late swing phase as the hamstrings work to decelerate the limb (Schache *et al.*, 2012; Yu *et al.*, 2008). There is however some opposing thought with regards to whether an eccentric contraction occurs in the late swing phase of high-speed running, with some evidence suggesting isometric work of the contractile element of the hamstrings and lengthening of the passive component during this period (Van Hooren and Bosch, 2017a). Such discrepancies may influence exercise selection and training strategies which are important for performance and injury prevention (van den Tillaar *et al.*, 2017). Exercise selection is further influenced by a growing body of evidence showing that hamstring activity differs during different exercises (Tsaklis *et al.*, 2015; Zebis *et al.*, 2013) and different phases of exercises (Bourne *et al.*, 2017b). This is likely to be a consequence of individual hamstring morphology, architecture and function (Kellis *et al.*, 2012; Thelen *et al.*, 2005b). While different muscle activity has been shown during distinct phases of exercises, the significance of the total amount of hamstring activity in encouraging muscle adaptations should not be disregarded (Hegyi *et al.*, 2019). It has been argued that hamstring exercises should mirror the injury risk phase of sprinting to enhance the effectiveness of injury prevention programmes (Malliaropoulos *et al.*, 2012; Guex *et al.*, 2016). While this approach would consider the range of movement and load experienced, it would not take in to account the identified risk factors for HSI, including muscle weakness, which is one of the most common factors associated with HSI risk (van den Tillaar *et al.*, 2017).

To better inform hamstring injury prevention practices, other lower limb muscles are worthy of consideration. These include the GM muscle due its role as a hip extensor and the importance of the synergistic function of the posterior chain to preclude hamstring muscle overload and injury (Schuermans *et al.*, 2017a). A history of previous calf injury increases HSI risk by up to 50% (Green *et al.*, 2020) and therefore analysing the activation of the gastrocnemius in terms of its role as a knee flexor, in addition to the hamstrings may provide evidence to further inform injury prevention programmes. Finally, evaluating RF activity will serve to provide information about the antagonistic role of the muscle during different hamstring exercises.

The clinical relevance and implications of analysing hamstring activation is related to the relatively unchanged incidence of HSI rates which has increased over the last two decades and remain high (Ekstrand *et al.*, 2016), thus questioning the effectiveness of current injury prevention strategies and prompting the need for further investigation. The primary cause of strain injury is reported to be the amount of strain that the muscle experiences and this may be controlled by muscle activation (Hegyi *et al.*, 2019a). Therefore, identifying exercises which maximally activate the hamstrings are likely to better prepare the muscles to cope with the demands of sprinting and thus could assist physiotherapists and coaches in the development of injury prevention and rehabilitation training programmes. Therefore, the aim of this study was to examine lower limb muscle activity during different hamstring strength training exercises.

5.2 Methods

5.2.1 Experimental procedures

Ten male rugby union players (mean ± SD: age = 22.9 ± 2.9 years; height = 1.83 ± 0.54 m; mass = 94.5 ± 9.6 kg) from an international sevens team were recruited for the study. Players had to meet the following inclusion criteria: 1) have no history of lower limb injury that has caused more than five days absence from training or matches in the last six months; 2) have no history of lower limb surgery; 3) be aged between 18-30 years old; 4) be injury free and healthy at the time of data collection and 5) be selected for the Wales sevens team at the time of testing. This study was approved by the Cardiff School of Sport and Health Sciences Ethics committee (Appendix 1) and all participants were given an information sheet (Appendix 2) and provided written informed consent prior to data collection (Appendix 3). All participants completed two repetitions of six hamstring exercises and sEMG was used to quantify lower limb muscle activity in the right leg during all exercises. The right leg was used for all participants regardless of limb dominance (Higashihara *et al.*, 2015a; Ono *et al*., 2015). For specific details regarding sEMG procedures, exercise protocol and data analysis see chapter 3.

5.2.2 Data collection

All participants wore their own trainers, socks, shorts and vests during data collection. Each participant completed the same testing protocol which included a 20-minute warm-up, the placement of sEMG electrodes and two repetitions of six different hamstring exercises. The activity of BFlh, ST, RF, GM and MG was recorded using a portable sEMG system as per the description in chapter 3. Lower limb dominance is reported to have no significant effect on hamstring muscle strain in professional rugby (Brooks *et al.*, 2006; Fuller *et al.*, 2011) hence the right leg was chosen for testing across all participants.

5.2.3 Surface electromyography normalisation procedures

The iEMG and peak amplitude of the first stride during the maximum velocity phase (30 – 40 m) of each participant's fastest sprint trial from study one was used for normalising the sEMG data for the second repetition of each exercise analysed (Suarez-Arrones *et al.*, 2019). The normalised sEMG signal for the exercise data was quantified via three methods: peak muscle activity, iEMG and co-activation muscle ratios of nEMG peak activity and iEMG during the performance of each of the six exercises. All data presented in the results and discussion therefore represent normalised values.

5.2.4 Exercise protocol

The exercises analysed and the protocol used are detailed in chapter 3. Two repetitions of each exercise were performed with video data recorded and sEMG data collected for each muscle accordingly. All exercises were performed in a random order so that there was no biasing of data and to reduce any order of effect due to fatigue.

5.2.5 Statistical analyses

The data were analysed using SPSS 24.0 software. A Shapiro-Wilk test showed that the majority of the data was normally distributed and subsequently a two-way ANOVA with repeated measures (5 x 6; muscle [BFlh; ST; RF; GM; MG] x exercise [NHE; single leg prone hamstring curl; single leg bridge; single leg Roman chair hold body weight; single leg Roman chair with 20kg; slider]) was used to compare the means between the participants that were divided based on two within-subjects factors (O'Donoghue, 2012). The level of statistical significance was set at $p \leq 0.05$. If sphericity was violated according to Mauchly's test, then the Greenhouse-Geisser adjustment was applied and if a non-significant result was obtained from this adjustment, then the Huynh-Feltd correction was used. If the ANOVA showed significant interactions or main effects then Bonferroni's *post hoc* analysis was used (Higashihara *et al.*, 2018; McAllister et *al.*, 2014; van den Tillaar *et al.*, 2017).

Results are presented as means ± SD and partial eta squared was used to assess the effect sizes, using $0.01 < \eta^2 < 0.06$ as a small effect, $0.06 < \eta^2 < 0.14$ as a medium effect and > 0.14 η^2 as a large effect (van den Tillaar *et al.*, 2017). Additionally, the magnitude of difference between variables for the pairwise comparisons was determined via Cohen's *d* effect size statistics, as the study aimed to understand which exercise activated each muscle to the greatest degree. The criteria used were trivial (d = ≤ 0.2), small (d = 0.2-0.49), medium (d = 0.5-0.79) and large ($d \geq 0.80$) effect sizes (Cohen, 1992).

5.3 Results

Due to some technical difficulties with the synchronisation of the LEDs with the Vicon system and some electrode movement, it was only possible to use data from seven participants in the analysis of peak muscle activity and five participants in the analysis of iEMG.

5.3.1 Normalised peak muscle activity

Table 5.1 shows the nEMG peak activity for all muscles during the hamstring exercises analysed and the effect sizes for within muscle comparisons. For peak nEMG, a significant interaction was observed for exercise and muscle ($F_{20,120}$ = 5.19, $p \leq 0.001$, η^2 = 0.464). Peak activity showed a significant main effect for exercise ($F_{5,30}$ = 3.55, p = 0.012, η^2 = 0.372) and *post-hoc* analysis indicated significantly higher peak activity during the single leg Roman chair hold bar compared to the single leg Roman chair hold body weight exercise (p = 0.018). Peak activity also showed a significant main effect for muscle ($F_{4,24}$ = 14.14, $p \leq 0.001$, η^2 = 0.702) and *post-hoc* analysis indicated that RF activity was significantly lower than BFlh (p = 0.010), ST (p = 0.020) and GM (p = 0.003).

Table 5.1 Normalised (%) peak activation (mean ± SD), significant differences and Cohen's *d* effect size for lower limb muscles during hamstring exercises (shading identifies the highest peak activation and the colour represents the effect size between the highest and second highest level of activation).

Exercise	BFlh peak activation	ST peak activation	RF peak activation	MG peak activation	GM peak activation
NHE	79 ± 36	68 ± 26	5 ± 4[ab]	41 ± 35	30 ± 18
PHC	86 ± 18	82 ± 24	6 ± 2[ab]	56 ± 32[*]	11 ± 8[ab]
SLB	88 ± 30	71 ± 30	4 ± 2[abc]	32 ± 31	32 ± 19
SLRCH_BW	81 ± 65	50 ± 48	5 ± 3[c]	18 ± 27	62 ± 32[^¥]
SLRCH_BAR	123 ± 80[*]	76 ± 74	8 ± 6[c]	32 ± 41	111 ± 41[^¥*ł]
SLID	87 ± 40	64 ± 28	6 ± 2[abc]	28 ± 24	47 ± 11[¥]

Key: a = significantly different to BFlh; b = significantly different to ST; c = significantly different to GM; ^ = significantly different to NHE; ¥ = significantly different to PHC; ł = significantly different to SLB; * = significantly different to SLRCH_BW. Biceps femoris long head (BFlh); semitendinosus (ST); rectus femoris (RF); medial gastrocnemius (MG); gluteus maximus (GM). Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID)

Within muscle effect size

- (green) Highest nEMG peak amplitude with a trivial effect size between the second highest nEMG peak value
- (orange) Highest nEMG peak amplitude with a medium effect size between the second highest nEMG peak value
- (grey) Highest nEMG peak amplitude with a small and medium effect size between the second highest nEMG peak value
- (yellow) Highest nEMG peak amplitude with a large effect size between the second highest nEMG peak value

5.3.2 Within exercise differences

Table 5.1 illustrates the significant findings for peak muscle amplitude observed within individual exercises. The NHE and single leg prone hamstring curl recruited BFlh and ST to a similar level and demonstrated higher peak amplitude compared to RF (NHE BFlh > RF p = 0.011; d = 1.62; ST > RF p = 0.006; d = 1.71; single leg prone hamstring curl BFlh > RF $p \leq 0.001$; d = 2.22; ST p = 0.002; d = 2.47). The single leg prone hamstring curl also resulted in greater BFlh and ST peak amplitude when compared to GM (BFlh > GM $p \leq 0.001$; d = 3.73; ST > GM p = 0.003; d = 2.79). The single leg bridge and slider showed higher BFlh and ST peak amplitude compared to RF (single leg bridge BFlh > RF p = 0.003; d = 2.89; ST > RF p = 0.009; d = 2.26; slider BFlh > RF p = 0.017; d = 2.02; ST > RF p = 0.013; d = 1.93). The slider also resulted in a higher peak amplitude for GM compared to RF ($p \leq 0.001$; d = 3.59). The single leg Roman chair hold body weight and bar exercises caused a higher GM peak amplitude compared to RF (single leg Roman chair hold body weight p = 0.032; d = 1.82; single leg Roman chair hold bar p = 0.005; d = 2.54).

Cohen's *d* calculations were computed for the peak nEMG data for individual exercises. Within each exercise the greatest level of peak activation was always observed in the BFlh. For the single leg prone hamstring curl there was only a trivial mean difference between BFlh and ST activation while for the single leg Roman chair hold bar there was only a trivial mean difference between BFlh and GM. In the case of the latter comparison, it was also evident that BFlh and GM peak activation during the single leg Roman chair hold bar exercise were the only instances where mean values exceeded 100%, demonstrating that this exercise produced BFlh and GM activity levels that were higher than those during sprinting (Table 5.1). A large mean difference was observed between BFlh and ST during the single leg Roman chair hold bar exercise and a medium difference between GM and ST during the same exercise. During the single leg bridge the BFlh muscle demonstrated the higher peak activity compared to ST and a small mean difference was observed. The slider resulted in a large difference between BFlh and ST. Figure 5.1 illustrates the relatively higher BFlh activity compared to ST across all exercises. While not significantly different, this confirms that these exercises elicit greater activation in BFlh and that the single leg Roman chair hold bar exercise results in the highest level of peak activity for the lateral hamstring.

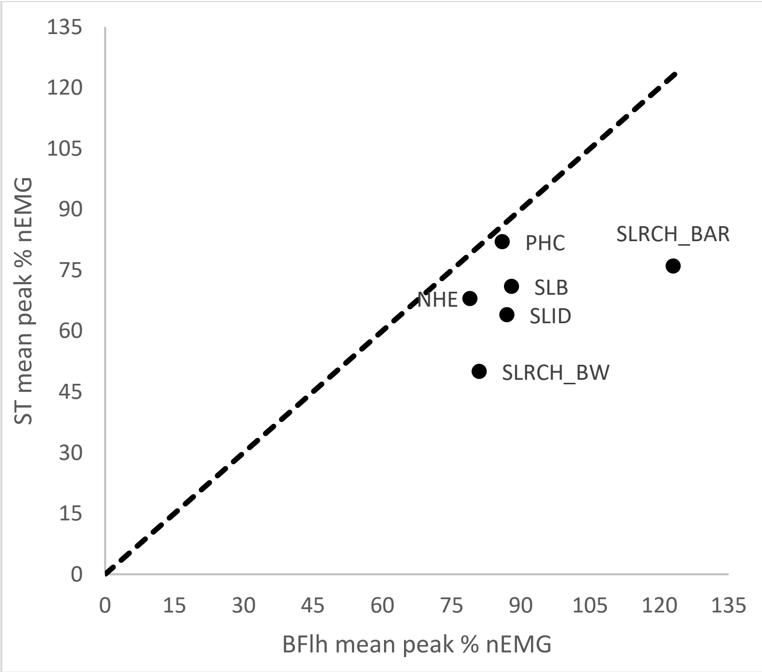

Figure 5.1 Biceps femoris long head peak activity (BFlh, % nEMG) compared to semitendinosus (ST, % nEMG) during six hamstring exercises. (Exercises below the line exhibited higher levels of BFlh activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

While no significant differences were observed for BFlh or ST versus GM activity, further illustration of BFlh and ST peak activity compared to GM is presented in figures 5.2 and 5.3 to depict the activity of the hip extensors. Figure 5.2 shows that BFlh activity was higher than GM during all exercises and that both muscles demonstrated their highest level of activity during the single leg Roman chair hold bar exercise. Semitendinosus activation however was lower than GM during the single leg Roman chair hold body weight and bar exercises, and it remained higher than GM during the other exercises, with the single leg prone hamstring curl producing the greatest level of ST peak activation (Figure 5.3).

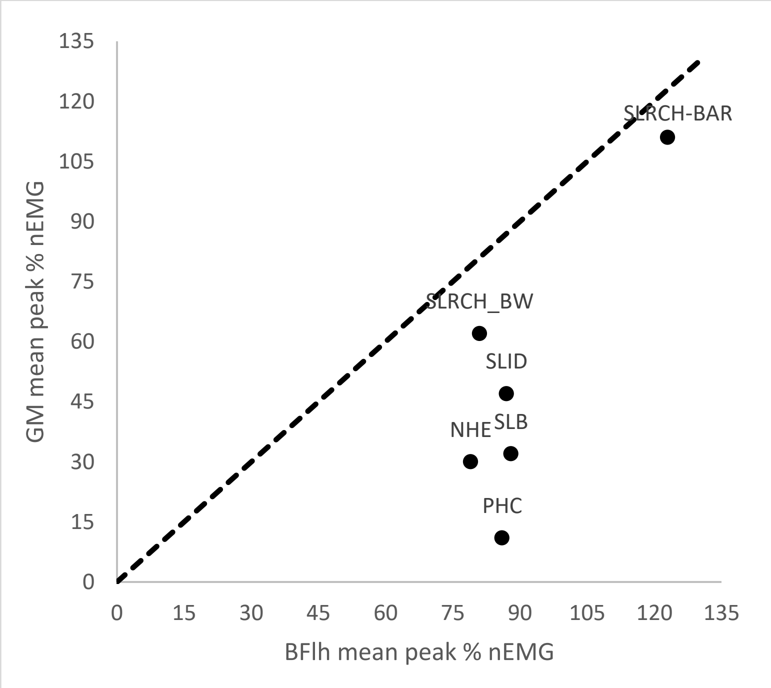

Figure 5.2 Biceps femoris long head peak activity (BFlh, % nEMG) compared to gluteus maximus (GM, % nEMG) during six hamstring exercises. (Exercises below the line exhibited higher levels of BFlh activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

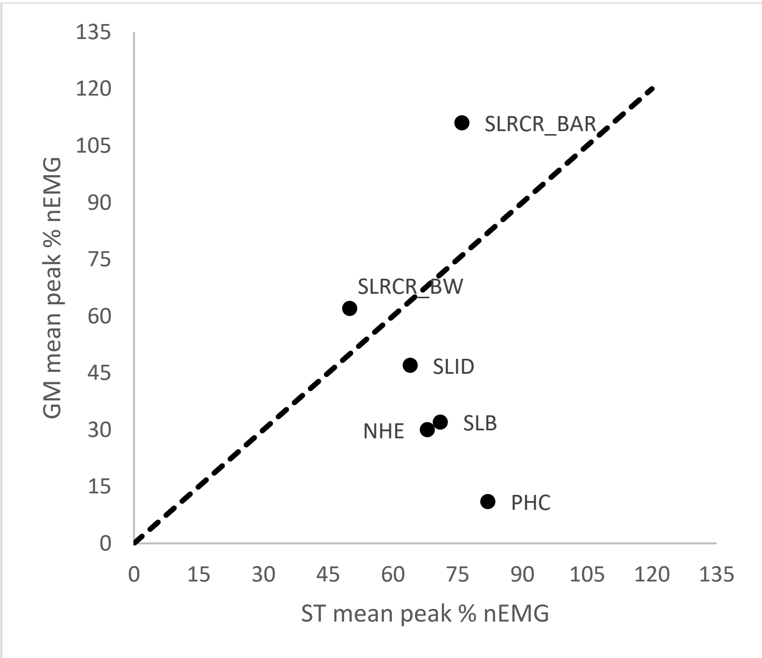

Figure 5.3 Semitendinosus peak activity (ST, % nEMG) compared to gluteus maximus (GM, % nEMG) during the six hamstring exercises. (Exercises below the line exhibited higher levels of ST activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

5.3.3 Within muscle differences

Table 5.1 summarises the statistically significant findings for the individual muscle peak activity observed across all exercises. Gluteus maximus was the muscle that demonstrated the most differences in peak activation across exercises. Gluteus maximus peak activity was higher during the single leg Roman chair hold body weight compared to the NHE (p = 0.044; d = 1.84) and PHC (p = 0.030; d = 1.50), higher during the single leg Roman chair hold bar compared to the single leg prone hamstring curl (p = 0.004; d = 2.86), single leg bridge (p = 0.025; d = 2.06) and single leg Roman chair hold body weight (p = 0.015; d = 0.97). Gluteus maximus peak activity was also higher during the slider compared to the single leg prone hamstring curl (p = 0.005; d = 2.25). Biceps femoris long head peak activation was higher during the single leg Roman chair hold bar compared to the single leg roman chair hold body weight (p = 0.023; d = 2.04). Medial gastrocnemius peak activity was higher during the single leg prone hamstring curl compared to the single leg Roman chair hold body weight (p = 0.044; d = 1.87). Non-significant differences for between exercise comparisons were found for the ST and RF.

Cohens *d* calculations were computed for the peak nEMG data for individual muscles. For the exercises which caused the largest and second largest nEMG peak activity, within individual muscle comparisons revealed that there was a medium difference between the means for the single leg Roman chair hold bar and single leg bridge exercises for BFlh activity, and a trivial difference between the means of ST activity during the single leg prone hamstring curl and the single leg Roman chair hold bar. Gluteus maximus activity was at its greatest during the single leg Roman chair hold bar exercise with a large difference between the means for this and that for the single leg Roman chair hold body weight exercise.

Medial gastrocnemius activity was at its highest during the single leg prone hamstring curl with a medium difference between the means of this exercise and the NHE being observed, while for RF the highest peak occurred during the single leg Roman chair hold bar exercise with the slider and single leg prone hamstring curl causing the second highest value, showing a small and medium difference between the mean values for these exercises respectively (Table 5.1). Table 5.1 also identifies that the highest activity for each muscle occurred in a difference exercise, with the NHE being the only exercise which did not provide the greatest stimulus for any muscle.

5.3.4 Normalised integrated EMG

Table 5.2 shows the niEMG for all muscles during the hamstring exercises and the effect sizes for within muscle comparisons. For niEMG, a significant interaction was observed for exercise and muscle ($F_{20,120} = 3.11$, $p \leq 0.001$, $\eta^2 = 0.437$). Integrated activity did not show a main effect for exercise ($F_{5,20} = 1.77$, $p = 0.167$, $\eta^2 = 0.306$) however a significant main effect was observed for muscle ($F_{4,16} = 22.41$, $p \leq 0.001$, $\eta^2 = 0.833$). *Post-hoc* analysis indicated that RF activity was significantly lower than BFlh ($p = 0.027$), ST ($p = 0.031$), MG ($p = 0.038$) and GM ($p = 0.023$) and MG activity was significantly lower than BFlh ($p = 0.039$).

Table 5.2 Normalised (%) iEMG (mean ± SD), significant findings and Cohen's *d* effect size for lower limb muscles during hamstring exercises (shading identifies the highest peak activation and the colour represents the effect size between the highest and second highest level of activation).

Exercise	BFlh niEMG	ST niEMG	RF niEMG	MG niEMG	GM niEMG
NHE	535 ± 303	539 ± 393	24 ± 68	155 ± 123	211 ± 96
PHC	592 ± 92	573 ± 153	35 ± 14[ab]	189 ± 130[a]	53 ± 21[ab]
SLB	752 ± 253	614 ± 205	29 ± 9[ab]	159 ± 84	327± 155
SLRCH_BW	529 ± 376	309 ± 205	32 ± 23	25 ± 22	384 ± 306
SLRCH_BAR	840 ± 494	479 ± 274	29 ± 16	92 ± 44	776 ± 320
SLID	585 ± 349	471 ± 213	37 ± 5[c]	116 ± 35	401 ± 133

__Key:__ a = significantly different to BFlh; b = significantly different to ST; c = significantly different to GM. Biceps femoris long head (BFlh); semitendinosus (ST); rectus femoris (RF); medial gastrocnemius (MG); gluteus maximus (GM). Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID)

Within muscle effect size

Highest niEMG within the muscle with a trivial effect size between the second highest value (green: PHC MG, SLB ST, SLID RF)

Highest niEMG within the muscle with a small effect size between the second highest value (blue: SLRCH_BAR BFlh)

Highest niEMG within the muscle with a large effect size between the second highest value (yellow: SLRCH_BAR GM)

5.3.5 Within exercise differences

Table 5.2 shows the significant findings observed for niEMG within individual exercises. The single leg prone hamstring curl and single leg bridge recruited BFlh and ST to a similar degree and demonstrated higher niEMG compared to RF (single leg prone hamstring curl BFlh > RF $p = 0.002$; $d = 5.79$; ST > RF $p = 0.013$; $d = 3.57$; single leg bridge BFlh > RF $p = 0.030$; $d = 2.88$; ST > RF $p = 0.036$; $d = 2.75$). The single leg prone hamstring curl also resulted in higher BFlh and ST niEMG when compared to GM (BFlh > GM $p = \leq 0.001$; $d = 6.48$; ST $p = 0.013$; $d = 3.57$), and the BFlh also showed greater niEMG when compared to MG during the prone hamstring curl (BFlh > MG $p = 0.032$; $d = 5.33$).

Cohens *d* calculations were computed for the niEMG data for individual exercises. Within exercise analysis showed that the NHE caused the highest niEMG in ST, however there was only a trivial mean difference between the ST and BFlh ($d = 0.01$). While the difference between the niEMG of the hamstrings and GM during the NHE did not reach statistical significance, there was a large magnitude of difference between the BFlh and GM ($d = 0.93$) and ST and GM ($d = 0.82$). Furthermore, a large effect size was observed between BFlh and MG ($d = 1.43$) and ST and MG ($d = 0.96$) during the NHE.

For the remaining five exercises the highest niEMG was observed in BFlh however, there was only a trivial mean difference between BFlh and ST during the single leg prone hamstring curl ($d = 0.11$) and BF and GM ($d = 0.16$) during the single leg Roman chair hold bar exercise. The single leg Roman chair hold bar exercise, as was the case for peak activity, resulted in the greatest amount of activity in BFlh and GM (Table 2). Figure 5.4 illustrates the higher niEMG demonstrated by BFlh in the majority of exercises when compared to ST. While a significant difference was not observed, this confirms that these exercises elicit greater activation in BFlh and that the single leg Roman chair hold bar exercise results in the highest level of activity for the lateral hamstring. With the exception of the NHE, this pattern of higher BFlh niEMG mirrors that observed for normalised BFlh peak activity levels.

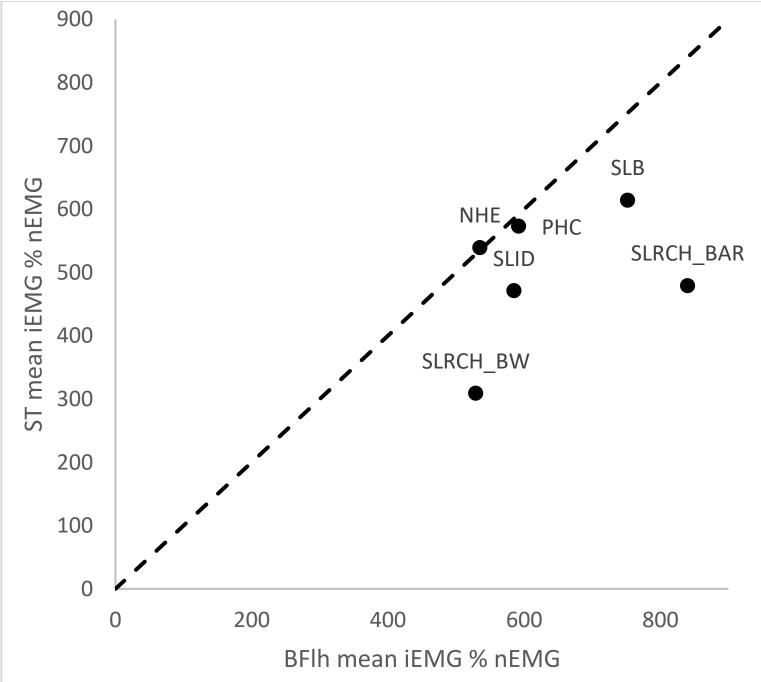

Figure 5.4 Biceps femoris long head iEMG (BFlh, % niEMG) compared to semitendinosus iEMG (ST, % niEMG) during the six hamstring exercises. (Exercises below the line exhibited higher levels of BFlh activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

While no significant differences were observed for BFlh or ST versus GM activity, figures 5.5 and 5.6 illustrate the activity of the hip extensors. Biceps femoris long head activity was higher than GM during all exercises and both muscles demonstrated their highest level of niEMG during the single leg Roman chair hold bar exercise (Figure 5.5). This mirrors the findings for peak activity levels for BFlh and GM (Figure 5.3). Semitendinosus versus GM activation is illustrated in figure 5.6 and shows that ST activity was lower than GM during the single leg Roman chair hold body weight and bar exercises, however the remaining exercises elicited higher ST activity compared to GM – these findings mirror those for ST peak activity (Figure 5.4). The single leg bridge produced the greatest ST niEMG (Figure 5.6).

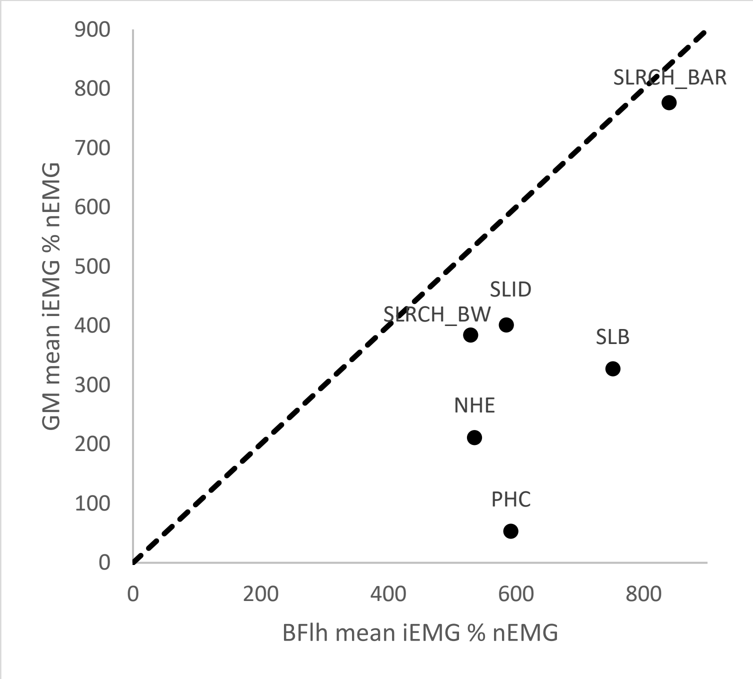

Figure 5.5 Biceps femoris long head iEMG (BFlh, % niEMG) compared to gluteus maximus iEMG (GM, % niEMG) during the six hamstring exercises. (Exercises below the line exhibited higher levels of BFlh activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

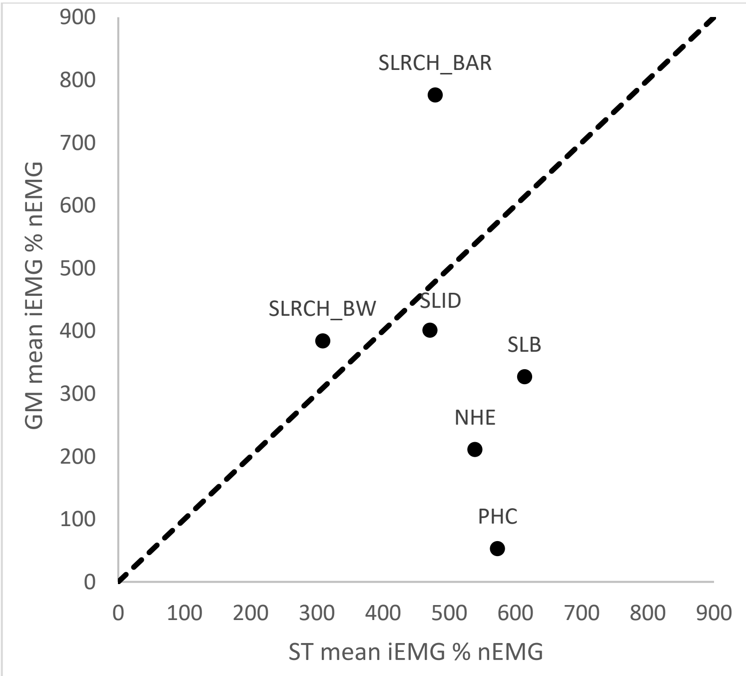

Figure 5.6 Semitendinosus iEMG (ST, % niEMG) compared to gluteus maximus iEMG (GM, % niEMG) during the six hamstring exercises. (Exercises below the line exhibited higher levels of ST activity). NHE = Nordic hamstring exercise; PHC = prone hamstring curl; SLB = single leg bridge; SLRCH_BW = single leg Roman chair hold with body weight; SLRCH_BAR = single leg Roman chair hold with 20kg bar; SLID = slider.

5.3.6 Within muscle differences

The niEMG did not show any significant differences within individual muscles. Cohens *d* calculations were computed for all niEMG data for individual muscles. Within individual muscle comparisons revealed that for the exercises which caused the largest and second largest niEMG activation there was a small difference between the means for BFlh during the single leg Roman chair hold bar and single leg bridge (*d* = 0.31), ST activity during the single leg bridge and single leg prone hamstring curl (*d* = 0.14) and MG during the single leg prone hamstring curl and single leg bridge (*d* = 0.18) and a large difference between the means for GM activation during the single leg Roman chair hold bar and slider exercises (*d* = 0.90). Rectus femoris activity was relatively low during all exercises compared to the other muscles analysed, however it was at its highest during the slider (Table 5.2), with only a trivial difference between the means for the slider and single leg prone hamstring curl (*d* = 0.16). Table 5.2 also shows that the highest niEMG for each muscle occurred in a difference exercise, with NHE being the only exercise which did not provide the greatest stimulus for any muscle.

5.3.7 Co-activation normalised peak activity

Table 5.3 shows the co-activation peak nEMG activity for all muscles during the hamstring exercises and the effect sizes for within muscle comparisons. For co-activation normalised peak activity a significant interaction between exercise and muscle was observed ($F_{20,120}$ = 3.96, $p \leq 0.001$, $n^2 = 0.398$). There was no main effect for exercise ($F_{5,30}$ = 1.52, $p = 0.214$, n^2 = 0.202) or muscle ($F_{4,24}$ = 3.86, $p = 0.082$ $n^2 = 0.392$).

Table 5.3 Normalised co-activation ratio peak activation (mean ± SD) and Cohen's *d* effect size of the lower limb muscles during hamstring exercises (shading identifies the highest peak activation and the colour represents the effect size between the highest and second highest level of activation).

Exercise	BFlhST co-activation peak activation	BFlhGM co-activation peak activation	STGM co-activation peak activation	BFlhMG co-activation peak activation	STMG co-activation peak activation
NHE	1.28 ± 0.54	3.49 ± 2.01	3.04 ± 2.22	3.05 ± 1.90	2.65 ± 1.89
PHC	1.14 ± 0.39	10.04 ± 5.42[a]	9.90 ± 6.83	2.07 ± 1.17	2.06 ± 2.12
SLB	1.48 ± 0.72	3.05 ± 2.51	2.03 ± 1.12	4.51 ± 2.38	3.67 ± 2.72
SLRCH_BW	1.76 ± 0.73	1.34 ± 0.80	0.90 ± 0.67	13.06 ± 16.00	11.64 ± 18.55
SLRCH_BAR	1.98 ± 0.90	1.11 ± 0.49	0.68 ± 0.49	6.95 ± 5.76	5.03 ± 5.62
SLID	1.46 ± 0.58	1.85 ± 0.84	1.36 ± 0.59	4.25 ± 2.23	3.05 ± 1.58

Key: a = significantly different to BFlhST. Biceps femoris long head (BFlh); semitendinosus (ST); rectus femoris (RF); medial gastrocnemius (MG); gluteus maximus (GM). Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID)

Within muscle effect size

Highest co-activation nEMG peak amplitude ratio with a small effect size between the second highest ratio value

Highest co-activation nEMG peak amplitude ratio with a large effect size between the second highest ratio value

5.3.8 Within exercise ratio differences

Table 5.3 summarises the significant findings observed for co-activation peak activity within individual exercises. The single leg prone hamstring curl exercise resulted in a higher BFlhGM ratio when compared to BFlhST (p = 0.049; d = 1.64), indicating the higher BF activity relative to GM when compared to BFlh activity relative to ST. No further significance between exercise comparisons were found. Cohen's d calculations were computed for the co-activation peak data for all exercises. The single leg prone hamstring curl resulted in the highest co-activation value for BFlhGM and STGM and there was only a trivial mean difference between these ratios (Table 5.3). Ratios >1.0 indicate that the BFlh and ST were more active than the GM during the single leg prone hamstring curl. The single leg Roman chair hold bar caused the greatest co-activity value in BFlhST with a large mean difference being observed between BFlhST and BFlhGM (d = 0.82). The lower co-activation ratio for BFlhGM during the single leg Roman chair hold bar exercise indicates more GM activity relative to BFlh when compared to the amount of ST activity relative to BFlh for this exercise. The highest co-activity ratio across all exercises occurred during the single leg Roman chair hold body weight exercise and was observed in the BFlhMG and there was a small mean difference between this and the STMG ratio (d = 0.37), thus confirming the greater activation of the hamstrings relative to the MG during this exercise (Table 5.3).

5.3.9 Within muscle ratio differences

Co-activation peak activity did not show any significant differences within individual muscle ratios. Cohen's d calculations were completed on the co-activation peak data for individual muscle ratios. Within muscle ratio comparisons revealed that the greatest BFlhST co-activation was observed during the single leg Roman chair hold bar and there was a large mean difference between the means for this exercise and the single leg Roman chair hold body weight exercise which caused the second highest BFlhST value (d = 0.80). The BFlhST co-activation for the single leg Roman chair hold bar and body weight exercises demonstrate a ratio of >1.0 indicating that the BFlh is more active than ST during these exercises (Table 5.3). The lowest BFlhST ratio was observed during the single leg prone hamstring curl, thus indicating that this exercise resulted in the most similar level of hamstring activity. The exercises which caused the highest and second highest co-activation for BFlhGM and STGM were the single leg prone hamstring curl and NHE respectively and there was a large difference (*d* = 1.07) between the means of these exercises. The findings demonstrate that BFlh and ST were more active than GM during both exercises however, the lower values of co-activity during the NHE signals that GM activity was greater relative to BFlh and ST during the NHE than that observed during the single leg prone hamstring curl. The co-activation for STGM during the single leg Roman chair hold body weight and bar exercises revealed lower ST activity relative to GM and are the only two exercises that resulted in lower hamstring activity when compared to GM. The largest BFlhMG and STMG ratios were a result of the single leg Roman chair hold body weight exercise with a small difference between the means for this and the single leg Roman chair hold bar exercise (*d* = 0.37 and *d* = 0.38 respectively). These findings suggest that MG activity was higher as a result of the addition of an external load. The lowest BFlhMG and STMG ratios occurred during the single leg prone hamstring curl highlighting that this exercise generated the highest MG activity relative to the hamstrings (Table 5.3).

5.3.10 Co-activation normalised integrated EMG

Table 5.4 summarises the co-activation niEMG for all muscles during the hamstring exercises analysed and the effect sizes for within muscle comparisons. For co-activation niEMG a significant interaction was observed between exercise and muscle ($F_{20,80}$ = 5.05, $p \leq 0.001$, η^2 = 0.558). Co-activation niEMG showed a significant main effect for exercise ($F_{5,20}$ = 3.05, p = 0.033, η^2 = 0.432) and muscle ($F_{4,16}$ = 8.20, $p \leq 0.001$, η^2 = 0.672) however, *post-hoc* analysis showed no significant differences between the exercise or muscle ratios.

Table 5.4 Normalised co-activation ratio iEMG (mean ± SD), significant differences and Cohen's *d* effect size of the lower limb muscles during hamstring exercises (shading identifies the highest peak activation and the colour represents the effect size between the highest and second highest level of activation).

Exercise	BFlhST co-activation niEMG	BFlhGM co-activation niEMG	STGM co-activation niEMG	BFlhMG co-activation niEMG	STMG co-activation niEMG
NHE	1.22 ± 0.61	3.10 ± 2.51	2.98 ± 2.86	4.87 ± 3.48	4.60 ± 3.71
PHC	1.08 ± 0.27	9.85 ± 3.48	9.57 ± 4.22	2.88 ± 1.14	3.06 ± 2.12
SLB	1.36 ± 0.65	2.75 ± 1.66	2.25 ± 1.13	5.54 ± 2.60	5.41 ± 3.03
SLRCH_BW	1.73 ± 0.82	1.38 ± 1.07	0.92 ± 0.76	22.31 ± 15.54	19.00 ± 21.66
SLRCH_BAR	1.86 ± 0.83	1.18 ± 0.64[a]	0.71 ± 0.46[a]	9.30 ± 3.30	6.17 ± 3.54
SLID	1.24 ± 0.47	1.37 ± 0.36	1.17 ± 0.32	5.02 ± 2.60	4.18 ± 1.56

<u>**Key:**</u> a = significantly different to BFlhMG. Biceps femoris long head (BFlh); semitendinosus (ST); rectus femoris (RF); medial gastrocnemius (MG); gluteus maximus (GM). Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID)

Within muscle effect size

(orange) Highest co-activation niEMG ratio with a medium effect size between the second highest ratio value

(yellow) Highest co-activation niEMG ratio with a large effect size between the second highest ratio value

5.3.11 Within exercise ratio differences

Table 5.4 summarises the significant findings observed for co-activation niEMG within individual exercises. The single leg roman chair hold bar exercise resulted in a higher BFlhMG ratio when compared to BFlhGM and STGM (BFlhMG > BFlhGM $p = 0.029$; $d = 2.89$; BFlhMG > STGM $p = 0.027$; $d = 2.96$). No further significant differences were observed for within exercise comparisons. Cohen's *d* calculations were computed for the co-activation niEMG data for all exercises. Within exercise analysis showed that the single leg prone hamstring curl was the exercise that resulted in the highest co-activation niEMG value, and this was observed in the BFlhGM ratio. The second highest value for the single leg prone hamstring curl was demonstrated by STGM with a trivial effect ($d = 0.09$) being established between these two muscle ratios.

Ratios >1.0 indicate that the BFlh and ST were more active than the GM during the prone hamstring curl. The single leg Roman chair hold bar resulted in the lowest recorded ratio across all exercises analysed with this finding being evident for STGM (0.71), indicating that GM was more active during this exercise than the ST muscle. The single leg prone hamstring curl and single leg Roman chair hold body weight exercises resulted in the values that were closest to 1.0 (BFlhST 1.08 and STGM 0.92 respectively) thus illustrating that during these exercises the two muscles in the respective ratios demonstrated the most similar levels of activity. The single leg Roman chair hold body weight exercise resulted in the highest ratio across all exercises and this was observed in the BFlhMG ratio and the difference between this and the STMG ratio was small. These findings mirror those observed in the co-activation peak data and confirms the higher hamstring activation relative to MG activity (Table 5.4).

5.3.12 Within muscle ratio differences

Co-activation niEMG did not show any significant differences for any of the muscle ratios analysed. Cohen's *d* calculations were computed for the co-activation niEMG data for all muscle ratios. Within muscle ratio comparisons revealed that the greatest BFlhST co-activation was observed during the single leg Roman chair hold bar and there was a medium difference between the means for this and the single leg Roman chair hold body weight exercise which resulted in the second highest BFlhST ratio. The single leg prone hamstring curl caused the lowest BFST ratio, and thus was the exercise that demonstrated the most a comparable level of activation between the lateral and medial hamstring muscles (Table 5.4). The single leg prone hamstring curl and NHE were the exercises which caused the largest and second largest co-activation values for both BFlhGM and STGM ratios, and a large magnitude of difference for these muscle ratios (d = 1.45 and d = 2.25 respectively) was observed between these exercises (Table 5.4). The co-activation niEMG for STGM during the single leg Roman chair hold body weight and bar exercises revealed lower ST activity relative to GM and are the only two exercises that resulted in lower hamstring activity when compared to GM (Table 5.4). A similar pattern was observed for STGM peak co-activity.

The highest and second highest BFlhMG and STMG ratios were generated during the single leg Roman chair hold body weight and bar exercises respectively and there was a large and medium mean difference between these values respectively. Medial gastrocnemius activity relative to the hamstring muscles was higher during the single leg prone hamstring curl as the co-activation ratios were lower. A similar pattern was observed for the co-activation peak ratios and confirm that the hamstring muscles were more active than the MG during all exercises and that BFlh activation was higher than ST in comparison to MG (Table 5.4).

5.4 Study limitations

The starting sample size of the study (n = 10) was small, however it represented close to the total sample of national level athletes selected to represent the WRU sevens team at the time of data collection. Unfortunately, due to some technical difficulties with the Vicon system and synchronisation of the LEDs, the sample size in some of the data outputs was reduced further (iEMG n = 5; peak activity n = 7; co-activity iEMG n = 5; co-activity peak n = 7). While this resulted in a small sample size, other studies have used similar participant numbers (Oliver and Dougherty, 2009; Ono *et al.*, 2010; Ono *et al.*, 2011). The ability to detect significance will have been influenced by both sample size and the number of comparisons. The relatively small sample size may have resulted in an increase in type II error, and therefore the findings obtained may have been more descriptive of the population analysed if a larger sample size had been used. However, effect sizes were used to provide useful information that was less influenced by the small sample size.

Large standard deviations were observed during some of the other exercises analysed. Surface electromyography data can be variable (Fauth *et al.,* 2010) and therefore the lack of any sEMG reliability metrics could have contributed to the variation observed in the data and should be considered when interpreting the findings. Different training history and experience influence large variability in sEMG measurements and the subsequent large standard deviations (van den Tillaar *et al*., 2017), yet the participants in the current study were from the same elite rugby team and played regional rugby, thus suggesting that all had a similar training background and similarly high training age. Nevertheless, individual participant muscle strength and sprinting style may differ and thus influence the sEMG data recorded and the data normalisation procedures. Furthermore, individual muscle recruitment strategies may contribute to the variation observed. The right leg was used for all participants regardless of limb dominance which is a method that has been adopted previously (McAllister *et al.*, 2014; Youdas *et al.*, 2015) however it may underestimate or overestimate the muscle activity recorded. Conversely, how limb dominance is defined is debatable with examples including the kicking leg (Hegyi *et al.*, 2019a; Macdonald *et al.*, 2018), step leg (Tsaklis *et al.*, 2015) and jumping leg (Kobayashi *et al.*, 2013). Furthermore, limb dominance may be associated with a specific task or skill (McGrath *et al.*, 2016) and therefore relates to the context of a situation thus making it more challenging to assess and agree a definition.

The exercises performed in the current study were completed with either body weight or moderate load and therefore they may not reflect the loading of exercises required for clinical practice and injury prevention programmes. However, from a practical perspective, low loads should be prescribed initially and then progressed accordingly, therefore the loads used in the current study were deemed appropriate. The addition of external load would, however, be possible to all exercises to aid the aims and objectives of different phases of injury prevention training programmes and should be addressed in future studies. Finally, the participants were free from injury and therefore the results may not be directly applicable to injured athletes. Hamstring strain injury results in altered hamstring activation patterns (Bourne *et al.*, 2016) and architecture (Timmins *et al.*, 2015) and therefore injured and previously injured athletes may respond differently to strength training exercises.

5.5 Discussion

The aim of this study was to analyse and compare hamstring muscle activity during different hamstring exercises. All findings demonstrated a significant interaction ($p \leq 0.05$), and a large effect size ($\eta^2 \geq 0.14$) for exercise and muscle. Significant main effects for exercise and muscle were also observed for peak activity ($p \leq 0.05$) and co-activation niEMG ($p \leq 0.05$), while for niEMG, a significant main effect ($p \leq 0.001$) was observed for muscle only, and the co-activation peak data did not demonstrate any significant main effects. All significant main effects observed were associated with large effect sizes ($\eta^2 \geq 0.14$). In general, for pairwise comparisons, there were limited significant differences for either peak nEMG, niEMG or co-activation. However, significance was observed for BFlh and GM activity during the single leg Roman chair hold bar exercise when compared to the body weight version, and this was the exercise that caused the highest normalised peak activity and iEMG for these muscles. Biceps femoris long head and ST were significantly more active than GM during the single leg prone hamstring curl, and the exercises which resulted in the greatest ST peak activity and niEMG were the single leg prone hamstring curl and single leg bridge respectively. The findings for the co-activation data showed that the BFlh to ST ratio was at its highest during the single leg Roman chair hold bar exercise while the single leg prone hamstring curl resulted in the greatest hamstring to GM ratios. The findings demonstrated relatively low RF activation during all exercises when compared to the other muscles and therefore it was decided that the RF muscle would not be included in the discussion of findings.

While the current findings can be compared to published literature, some caution is needed given the confounding effect of different experimental techniques used. These include sEMG data normalisation procedures (Hegyi *et al.*, 2019a; McAllister *et al.*, 2014; Zebis *et al.*, 2013); ST sEMG sensor placement (McAllister *et al.*, 2014; van den Tillaar *et al.*, 2017); participant sex (Tsaklis *et al.*, 2015; Zebis *et al.*, 2013); participant background (Bourne *et al.*, 2017b; van den Tillaar *et al.*, 2017); differences in exercise loads (Andersen *et al.*, 2006) and prescription (Bourne *et al.*, 2017b; Tsaklis *et al.*, 2015). Furthermore, the use of fMRI (Bourne *et al.*, 2017b; Bourne *et al.*, 2018b; Mendiguchia *et al.*, 2013b) versus sEMG needs be considered. Functional magnetic resonance imaging is used post-exercise and measures metabolic activity of muscles and not the amplitude of muscle activity (Fernandez-Gonzalo *et al.*, 2016), while sEMG provides information about both spatial and temporal elements of the muscle during activity (Cagnie *et al.*, 2011).

It should also be acknowledged that some studies have reported the amplitude of muscle activity during different exercise phases (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a; McAllister *et al.*, 2014). However, for exercises that traditionally do not have an isolated eccentrically biased phase, such as the single leg prone hamstring curl, it seems reasonable to propose that the muscle activation throughout the exercise is the key focus. Hence, the overall hamstring amplitude was the focus of the current investigation. Indeed, recent literature proposes that exercises that generate high overall hamstring muscle amplitude are likely to be of most importance to encourage muscle adaptations (Hegyi *et al.*, 2019a).

5.5.1 Biceps femoris long head and semitendinosus activation

There was no significant difference between the BFlh and ST muscles during any of the exercises. However, the findings highlighted a bias towards BFlh activation across all exercises. While the NHE is advocated for hamstring training and injury prevention (Bourne *et al.*, 2017b), the current findings show that the hamstring muscles demonstrate greater activation during other exercises. The BFlh in particular demonstrated its lowest peak and second lowest niEMG values during the NHE, while for the ST the NHE generated the fourth and third highest normalised peak and iEMG values respectively (Tables 5.1 and 5.2). The finding of a similar pattern of hamstring activation during the NHE mirrors the lack of significance between hamstring differences shown by previous research (Iga *et al.*, 2012; Tsaklis *et al.*, 2015; van den Tillaar *et al.*, 2017; Zebis *et al.*, 2013). Conversely, others have reported a preferential recruitment of ST during the NHE (Bourne *et al.*, 2017b; Mendiguchia *et al.*, 2013b; Messer *et al.*, 2018), however the latter studies adopted fMRI analysis, which influences direct comparison to sEMG studies.

In conjunction with the lower hamstring activation generated in the current study, the NHE trains the hamstrings at short MTU lengths with no movement at the hip (Ditroilo *et al.*, 2013) and thus is in contrast to the longer hamstring muscle-tendon lengths which occur during high-speed running (Chumanov *et al.*, 2007; 2011). Collectively these findings suggest that the potential for hamstring strengthening with the NHE may be less in comparison to other exercises and thus may not be the most effective exercise for hamstring training and injury prevention. However, it is pertinent to note that the current findings are based on muscle activation alone and do not consider other factors such as the generation of force during the exercises analysed. The NHE has been shown to be generate higher force when compared to other exercises (Van Hooren *et al.,* 2022) and the benefits of the exercise as part of hamstring training programmes and addressing injury risk have been established (Ripley *et al.,* 2023; Van Dyk *et al.,* 2019). Therefore, while the patterns of activation in the current study illustrate the potential benefits of other exercises, the consideration of other factors in addition to muscle activation must not be disregarded.

Biceps femoris long head and ST activity was similar during the single leg prone hamstring curl. It is important to acknowledge the use of the isokinetic dynamometer for this exercise as higher loads result in higher levels of sEMG activation (Vigotsky *et al.*, 2015; Bourne *et al.*, 2018a). However, the lack of significant difference in hamstring activity during the single leg prone hamstring curl has previously been observed using an isokinetic dynamometer (Zebis *et al.*, 2013) and also when using a percentage of one repetition maximum (RM) to determine the applied load (Wright *et al.*, 1999). The single leg prone hamstring curl generated the highest ST peak activation and second highest niEMG, which may be a consequence of this muscle being reported to be more active during knee-dominant exercises (Bourne *et al.*, 2017b). Contradictory to the current findings, significantly more ST activity relative to the BF during the single leg prone hamstring curl has previously been observed (McAllister *et al.*, 2014; Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a). The discrepancy in findings may be due to the methodological differences, including no reference to controlling limb position in the latter studies compared to the current study and previous work (Zebis *et al.*, 2013). Enhancing the ability of ST to endure load may encourage a more balanced response of the synergistic pairing of BFlh and ST during injury risk situations such as high-speed running (Schuermans *et al.*, 2014). Furthermore, the significance of ST in hamstring injury prevention and rehabilitation by offloading the BFlh has recently been argued (Giakoumis, 2020). Therefore, the ST activation observed in the current study suggests that further investigation of the prone hamstring curl as part of hamstring injury prevention is warranted.

The slider is a single limb exercise focusing on eccentric knee flexion while the hip is in a bridge position. Similar hamstring activation patterns were observed during the slider, which mirrors previous findings (Orishimo and McHugh, 2015). Zebis and colleagues (2013) report significantly greater BFlh activity compared to ST, which may be due to differences in the slider exercise analysed when compared to the current study. The current data indicates that when compared to some of the other exercises, the slider resulted in lower ST activity while BFlh activation was relatively higher, however the exercise does not appear to the most optimal exercise to target hamstring activation.

The single leg bridge involves the hip and knee joints and generated high activation for both hamstrings in the current study, however greater BFlh activity relative to ST was observed and a medium magnitude of difference recorded. The duration of one repetition of the single leg bridge (six seconds) was longer than the single leg prone hamstring curl (four seconds). Therefore, while a longer duration produced higher BFlh activation, the same was not evident for the ST muscle, thus implying that exercise duration did not uniformly affect hamstring activation. Consequently, it appears reasonable to suggest that the single leg bridge is a beneficial exercise to target the BFlh muscle. On the other hand, the single leg prone hamstring curl may be a better choice when compared to the single leg bridge for ST training. The use of a single leg bridge with minimal knee flexion is supported by previous work completed by Askling and co-authors (2013; 2014) which recommends the use of exercises with the hamstrings in a lengthened position for hamstring strength development and rehabilitation (Schmitt *et al.*, 2012). The single leg bridge can be easily progressed by the addition of an external load and may augment the muscle activity observed in the current study, which would be beneficial for hamstring training.

Recent work argues that the contractile component of the hamstring muscles work in an isometric manner during the swing phase of high-speed running and that isometric-based exercise may be more effective for hamstring training (Van Hooren and Bosch, 2017b; 2018). Consequently, an exercise such as the single leg Roman chair hold requires consideration as it involves isometric hamstring contraction at the hip and knee (Van Hooren and Bosch, 2017b). In the current study, this exercise using the 20kg bar generated the highest BFlh activation when compared to the other exercises and the magnitude of difference in the means of BFlh versus ST peak activity and niEMG during the single leg Roman chair hold bar exercise was medium and small respectively. The co-activation ratios further confirm the higher BFlh activity; in particular, the peak activity ratio was the highest recorded for BFlhST across all exercises. Biceps femoris long head peak activity was 123% compared to the maximum activity in the sprint, which was considered as 100%, and was the highest level of activation observed for this muscle compared to the other exercises analysed. The short fibres of BFlh and the large pennation angle make it more suited to isometric muscle actions (Kubota *et al.*, 2007) and knee joint angle influences hamstring muscle niEMG; with BFlh demonstrating a greater amplitude between 15° - 30° knee flexion (Onishi *et al.*, 2002).

Therefore, the minimal knee flexion evident during the single leg Roman chair hold bar and single leg bridge exercises appear to contribute to the relatively higher BFlh activity compared to ST observed in the current study.

A recent study reports that a six-week isometric hamstring training programme including a single leg Roman chair hold exercise resulted in a considerable improvement in the strength-endurance capacity of the hamstring muscles when compared to the NHE (Macdonald *et al.*, 2018). The former exercise may encourage improved training adaptations as isometric muscle contractions generate a larger fatiguing stimulus when compared to isotonic contractions (Kay *et al.*, 2000). Consequently, this exercise may address a fatigue-induced mechanism of injury by improving muscle endurance which is one of the identified risk factors for HSI (Freckleton *et al.*, 2014; Schuermans *et al.*, 2016). Collectively, the high BFlh and ST peak activity observed in the current investigation suggests that the single leg Roman chair hold bar exercise is worthy of consideration to develop hamstring strength. Furthermore, the Roman chair hold is a single limb exercise, and the knee is in a position of minimal flexion which mirrors the limb position during the injury risk period of late swing, which suggests that it may be a beneficial exercise to consider in hamstring injury prevention programmes.

5.5.2 Gluteus maximus activation

The synergistic role of the posterior chain muscles to preclude hamstring overload in running is important (Schuermans *et al.*, 2017a) and the relationship between GM activation and weakness and HSI risk has previously been reported (Schuermans *et al.*, 2017a; Sugiura *et al.*, 2008). Furthermore, neuromuscular deficits in gluteal muscle activation may influence calf muscle strain (Bramah *et al.,* 2021) and a history of calf muscle injury increases the risk of HSI (Green *et al.,* 2020). Therefore, exercises which target GM and result in high activation need to be considered when addressing hamstring strain injury prevention and training programmes. The NHE and single leg prone hamstring curl resulted in the lowest GM activation, and statistical significance was observed between the lower GM peak activity and that of the BFlh and ST muscles during the single leg prone hamstring curl (Table 5.1). The isometric contraction of GM during the NHE to encourage posterior pelvic tilt and reduced activation as the knee moves towards extension (Narouei *et al.*, 2018), in conjunction with the knee dominant nature of the single leg prone hamstring curl explains these findings.

Consistent with previous research, there were no significant differences between the hamstring and GM peak amplitude during the single leg bridge (Andersen *et al.*, 2006; Youdas *et al.*, 2015). Similar results were observed during the slider exercise. The exercise that resulted in the highest GM activity was the single leg Roman chair hold bar exercise. Similar levels of BFlh and GM activity were observed during this exercise; with only a trivial mean difference between them. Additionally, the peak activity on average exceeded the 100% reference value obtained during sprinting. Gluteus maximus activity was greater than ST for both versions of the single leg Roman chair exercise and this was confirmed by co-activation ratios of <1.0 for STGM. Collectively the high GM activity generated during the single leg Roman chair hold bar exercise in conjunction with the high BFlh activity observed implies it may be an appropriate choice for hamstring injury prevention and warrants further investigation.

5.5.3 Medial gastrocnemius activation

Due to its role as a knee joint flexor, the current study included MG as it was considered relevant to explore the activation of this muscle along with the hamstrings. Relatively low MG activation was evident across all exercises when compared to the hamstrings, which may be due to the data being normalised to sprinting and thus demonstrates that the MG is not activated to the same extent during exercises as in sprinting. The findings of the current study show that the single leg prone hamstring curl generated the highest MG activation, and therefore as this exercise also resulted in the highest ST peak activation and second highest niEMG consideration of this exercise in HSI prevention programmes appears justified.

5.6 Conclusion

In the current study, BFlh activation was at its highest during the isometrically based single leg Roman chair hold bar exercise. The results show that, while popular in practice, the NHE did not demonstrate high levels of BFlh or ST activity when compared to some of the other hamstring exercises. The single leg Roman chair hold bar exercise also resulted in high ST and GM activity and therefore considering the inclusion of this exercise in hamstring injury prevention programmes and rehabilitation interventions appears appropriate. Furthermore, the BFlh and ST activity generated during the single leg bridge and prone hamstring curl suggests that these could be useful exercises incorporate in to hamstring training programmes.

Chapter 6: Prelude

Chapter 5 examined lower limb muscle activation patterns during different hamstring strength training exercises. The study identified that the single leg Roman chair bar generated the highest normalised BFlh peak and iEMG, and the peak activity of the muscle exceeded the 100% reference value of maximal velocity sprinting; a finding also observed in the GM muscle. Conversely, the highest ST activation occurred during the single leg prone hamstring curl and single leg bridge. Collectively, the findings confirmed those of previous research demonstrating differing hamstring muscle activation during strength training exercises.

The data obtained from chapter 5 adds to the existing research regarding hamstring activation patterns during training exercises, and also provides information about synergistic muscle activity which is not as commonly reported in the literature. There is minimal research that has examined the relationship between lower limb muscle activity during sprinting and different exercises. Such information could improve the specificity of hamstring training programmes and could help practitioners in the development of HSI prevention protocols. Therefore, chapter 6 examined the relationship between muscle activation during the early stance and late swing phases of maximal velocity sprinting and hamstring strength training exercises. However, it will need to be recognised that this work was conducted using a very small sample of elite WRU players, with no sEMG reliability data presented for the sample population.

Chapter 6

Lower limb muscle activation during sprinting and hamstring strength training exercises

6.1 Introduction

Hamstring strain injuries are the most common muscle injury in sport (Malliaropoulos *et al.*, 2011; Schmitt *et al.*, 2012) with sprinting being the main mechanism of injury (Guex and Millet, 2013; Heiderscheit *et al.*, 2010). The hamstrings demonstrate a biphasic pattern of peak activity during high-speed running; the first being observed in late swing and the second in the early stance phase (Chumanov *et al.*, 2011; Hegyi *et al.*, 2019b), and HSI is argued to occur in one of these two phases (Chumanov *et al.*, 2011; Orchard 2012) or during the transition period between both (Liu *et al.*, 2012). Hamstring strengthening exercises have been proposed to be a key part of HSI prevention (Bourne *et al.*, 2018a; Guex and Millet, 2013; Schmitt *et al.*, 2012), but there is a lack of agreement relating to the most effective exercises to perform.

The incidence of HSI has not decreased in recent years (Ekstrand *et al.*, 2016). This may be a consequence of a lack of hamstring exercise specificity and the use of exercises that do not expose the hamstrings to the demands placed upon them during sprinting (van den Tillaar *et al.*, 2017). Recent work demonstrates a heterogenous pattern of muscle activity during different hamstring exercises and consequently the use of hip extension-based exercises is advocated for strengthening BFlh and SM, while knee flexion-based exercises are recommended for the ST and BF short head muscles (Bourne *et al.*, 2018a). While knowledge of muscle activation facilitates the specificity of hamstring training, such findings do not identify which exercises are most specific to sprinting.

The hamstring muscles are most vulnerable during the late swing and early stance phases of sprinting (Kenneally-Dabrowski *et al.*, 2019b; 2019c; Liu *et al.*, 2012; Orchard, 2012). Therefore, the specificity of hamstring training could be enhanced by comparing muscle activation during these phases to that which occurs during hamstring training exercises. To date, few studies have investigated the sprint-specificity of hamstring exercises. A recent study by van den Tillaar and colleagues (2017) analysed and compared muscle activity during non-motorised treadmill sprinting and exercises that involved the hip and knee joints and targeted the hamstrings in a lengthened position. The results demonstrated that maximum BF and ST activity was greater during sprinting when compared to the exercises analysed. Similar findings have been reported when comparing hamstring activity during isometric, concentric and eccentric based exercises and over-ground sprinting (Prince *et al.*, 2021). Collectively, the exercises analysed in these studies failed to generate muscle activity levels that resemble those caused by sprinting.

Considering the persistent HSI rates in sport and the subsequent loss of time from training and competition (Brooks *et al.*, 2006; Liu *et al.*, 2012), further investigation is required to improve hamstring injury prevention practices. Due to the mechanism of HSI, encouraging specificity of training by identifying exercises which generate the closest hamstring function in terms of sEMG activity compared to sprinting is of particular interest from an injury prevention perspective. Additionally, such exercises may also serve to improve performance (Prince *et al.*, 2021). The amount of muscle activation in different hamstring exercises relative to the maximal velocity phase of sprinting has been established in a previous study (Chapter 5). Following on from the latter, the aim of this study is to examine the relationship between lower limb muscle activation during the early stance and late swing phases of the maximal velocity phase of sprinting and hamstring strength training exercises. The findings will help to inform exercise selection and will contribute to the development of hamstring injury prevention programmes.

6.2 Methods

The muscle activation during sprinting and six hamstring training exercises of five rugby union players (mean ± SD: age = 24 ± 3.4 years; height = 1.83 ± 7.8 m; mass = 92.4 ± 9.4 kg) from an international sevens team collected in two previous investigations (chapters 4 and 5) was compared in this study. For specific details regarding the inclusion criteria, sEMG procedures, exercise and sprinting protocols and data analysis of the previous studies, see chapter 3.

6.2.1 Statistical analysis

Pearson's correlation tests (*r*) with 95% confidence limit intervals were used to test the relationship between the muscle activity during sprinting and during the exercises. Scatter plots were visually inspected for outliers. Correlation co-efficients were interpreted using

Hopkin's threshold; $r = 1$ perfect correlation; $1 \geq r \geq 0.9$ nearly perfect; $0.9 \geq r \geq 0.7$ very large; $0.7 \geq r \geq 0.5$ large; $0.5 \geq r \geq 0.3$ moderate; $0.3 \geq r \geq 0.1$ small; $0.1 \geq r$ trivial. (Hopkins, 2000). The level of statistical significance was set at $p \leq 0.05$.

6.3 Results

6.3.1 Normalised peak activity

A positive correlation for peak activation was observed between the majority of exercises and both sprint phases (Table 6.1).

Table 6.1 Correlation analysis between normalised peak EMG during sprinting and hamstring exercises

Exercise – Sprint phase	**Pearson's r and lower and upper limits (95% CI)**			
	BFlh	**ST**	**GM**	**MG**
NHE - EST	0.01 (-0.88, 0.88)	-0.35[d] (-0.94, 0.77)	0.35 (-0.77, 0.94)	0.00 (-0.88, 0.88)
PHC - EST	0.26 (-0.81, 0.93)	0.92*[a] (0.18, 1.0)	0.04 (-0.87, 0.89)	-0.38[d] (-0.95, 0.75)
SLB - EST	-0.68[c] (-0.98, 0.50)	0.06 (-0.87, 0.89)	0.89*[b] (0.02, 0.99)	-0.32[d] (-0.94, 0.78)
SLRCH_BW - EST	-0.18 (-0.92, 0.84)	0.13 (-0.85, 0.91)	0.12 (-0.85, 0.91)	0.23 (-0.82, 0.92)
SLRCH_BAR - EST	-0.18 (-0.92, 0.83)	0.24 (-0.82, 0.93)	0.58[c] (-0.62, 0.97)	0.79[b] (-0.30, 0.99)
SLID - EST	-0.24 (-0.93, 0.81)	-0.19 (-0.92, 0.83)	-0.71[b] (-0.98, 0.46)	0.20 (-0.83, 0.92)
NHE - LSWING	0.54[c] (-0.66, 0.96)	-0.10 (-0.90, 0.86)	0.49[d] (-0.69, 0.96)	0.11 (-0.86, 0.91)
PHC - LSWING	0.08 (-0.86, 0.90)	0.87[b] (-0.05, 0.99)	-0.07 (-0.90, 0.87)	-0.28 (-0.93, 0.80)
SLB - LSWING	0.09 (-0.86, 0.90)	0.10 (0.14, 0.99)	0.74[b] (-0.41, 0.98)	-0.32[d] (-0.91, 0.85)
SLRCH_BW - LSWING	0.52[c] (-0.67, 0.96)	0.32[d] (-0.78, 0.94)	0.26 (-0.81, 0.93)	0.42[d] (-0.74, 0.95)
SLRCH_BAR - LSWING	0.58[c] (-0.62, 0.97)	0.43[d] (-0.73, 0.95)	0.41[d] (-0.74, 0.95)	0.90*[a] (0.09, 0.99)
SLID - LSWING	0.22 (-0.82, 0.92)	0.16 (-0.84, 0.91)	-0.87[b] (-0.99, 0.05)	0.40[d] (-0.75, 0.95)

__Key:__ Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID); EST – early stance; LSWING – late swing; * p = < 0.05; a = nearly perfect correlation ($1 \geq r \geq 0.9$); b = very large correlation ($0.9 \geq r \geq 0.7$); c = large correlation ($0.7 \geq r \geq 0.5$); d = moderate correlation ($0.5 \geq r \geq 0.3$)

6.3.2 Biceps femoris long head peak activity

A large negative correlation was found between the early stance phase and the single leg bridge and a large positive correlation between late swing and the NHE and the single leg Roman chair hold body weight and bar exercises. The remaining correlation coefficients for BFlh peak activity were small or trivial (0.3 $\geq$ r $\geq$0.1 small; 0.1 $\geq$ r trivial).

6.3.3 Semitendinosus peak activity

A nearly perfect, positive statistically significant correlation was found for ST peak activation between the single leg prone hamstring curl and the early stance phase [r = 0.92 (95% CI 0.18, 1.0); *p* = 0.03]. A moderate negative correlation was observed between the NHE and early stance phase. A very large positive correlation was found for ST peak activation between the single leg prone hamstring curl and the late swing phase. Semitendinosus peak activity during the single leg Roman chair hold body weight and bar exercises revealed a moderate positive correlation with late swing. All other ST peak activity correlations reached coefficients ranging from small to trivial (0.3 $\geq$ r $\geq$0.1 small; 0.1 $\geq$ r trivial).

6.3.4 Gluteus maximus peak activity

A very large positive statistically significant correlation was found for GM peak activation between the single leg bridge and the early stance phase [r = 0.89 (95% CI 0.02, 0.99); *p* = 0.045]. The single leg bridge also demonstrated a very large positive correlation with the late swing phase. Gluteus maximus peak activity during the single leg Roman chair hold bar exercise revealed a large positive correlation with early stance and a moderate positive correlation with the late swing phase. Moderate positive correlations were also evident between the NHE and both phases of the sprint. A very large negative correlation was found between early stance GM activity and the slider exercise. All other GM peak activity correlations reached coefficients ranging from small to trivial (0.3 $\geq$ r $\geq$0.1 small; 0.1 $\geq$ r trivial).

6.3.5 Medial gastrocnemius peak activity

A very large positive correlation was found between MG activity in the early stance phase and the single leg Roman chair hold bar exercise, and a nearly perfect, positive statistically significant correlation was observed between the single leg Roman chair hold bar exercise and the late swing phase [r = 0.90 (95% CI 0.092, 0.994); *p* = 0.04]. A moderate positive correlation was evident between the single leg Roman chair hold body weight and slider exercises and late swing. The single leg prone hamstring curl showed a moderate negative correlation with the early stance and late swing phase. The remaining MG peak activity correlation coefficients ranged from small to trivial ($0.3 \geq r \geq 0.1$ small; $0.1 \geq r$ trivial).

6.3.6 Normalised integrated EMG

The majority of the niEMG shows a negative relationship between the exercises and the early stance phase, while a positive relationship is shown between the majority of exercises and the late swing phase (Table 6.2).

Table 6.2 Correlation analyses between normalised integrated EMG during sprinting and hamstring exercises

Exercise – Sprint phase	Pearson's r and lower and upper limits (95% CI)			
	BFlh	ST	GM	MG
NHE - EST	-0.27 (-0.93, 0.81)	-0.28 (-0.93, 0.80)	0.28 (-0.80, 0.93)	0.08 (-0.86, 0.90)
PHC - EST	0.46[d] (-0.71, 0.95)	-0.27 (-0.93, 0.81)	-0.11 (-0.90, 0.86)	-0.11 (-0.91, 0.85)
SLB - EST	-0.57[c] (-0.97, 0.63)	-0.83[b] (-0.99, 0.20)	-0.23 (-0.92, 0.82)	-0.62[c] (-0.97, 0.58)
SLRCH_BW - EST	-0.47[d] (-0.96, 0.70)	-0.73[b] (-0.98, 0.44)	0.19 (-0.83, 0.92)	0.07 (-0.87, 0.90)
SLRCH_BAR - EST	-0.33[d] (-0.93, 0.78)	-0.78[b] (-0.99, 0.33)	0.44[d] (-0.72, 0.95)	0.42[d] (-0.74, 0.95)
SLID - EST	-0.08 (-0.90, 0.86)	-0.48[d] (-0.96, 0.70)	-0.88[b] (-0.99, 0.02)	0.07 (-0.87, 0.90)
NHE - LSWING	-0.29 (-0.93, 0.80)	0.69[c] (-0.49, 0.98)	0.39[d] (-0.75, 0.95)	-0.01 (-0.88, 0.88)
PHC - LSWING	0.02 (-0.88, 0.89)	0.82[b] (-0.23, 0.99)	0.17 (-0.84, 0.92)	-0.08 (-0.90, 0.86)
SLB - LSWING	0.51[c] (-0.68, 0.96)	0.34[d] (-0.78, 0.94)	-0.33[d] (-0.94, 0.78)	-0.44[d] (-0.95, 0.73)
SLRCH_BW - LSWING	0.51[c] (-0.67, 0.96)	0.13 (-0.85, 0.91)	0.32[d] (-0.78, 0.94)	0.31[d] (-0.79, 0.93)
SLRCH_BAR - LSWING	0.65[c] (-0.54, 0.97)	0.21 (-0.83, 0.92)	0.31[d] (-0.79, 0.94)	0.50[c] (0.68, 0.96)
SLID - LSWING	0.13 (-0.91, 0.85)	0.59[c] (-0.61, 0.97)	-0.65[c] (-0.97, 0.55)	0.20 (-0.83, 0.92)

Key: Nordic hamstring exercise (NHE); prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold body weight (SLRCH_BW); single leg Roman chair hold bar (SLRCH_BAR); slider (SLID); EST – early stance; LSWING – late swing; a = nearly perfect correlation ($1 \geq r \geq 0.9$); b = very large correlation ($0.9 \geq r \geq 0.7$); c = large correlation ($0.7 \geq r \geq 0.5$); d = moderate correlation ($0.5 \geq r \geq 0.3$)

6.3.7 Biceps femoris long head integrated EMG

A large negative correlation was found between the niEMG of BFlh during the early stance phase and the single leg bridge and a moderate negative correlation between the early stance phase and the single leg Roman chair hold body weight and bar exercises. A moderate positive correlation was observed between the BFlh niEMG during early stance and the single leg prone hamstring curl. The single leg bridge and single leg Roman chair hold body weight and bar exercises demonstrated a large positive correlation with the late swing phase. All other BFlh niEMG correlation coefficients ranged from small to trivial ($0.3 \geq r \geq 0.1$ small; $0.1 \geq r$ trivial).

6.3.8 Semitendinosus integrated EMG

A very large negative correlation was found between the early stance phase and the single leg bridge and single leg Roman chair hold body weight and bar exercises. The niEMG of ST during the early stance phase demonstrated a moderate negative correlation with the slider exercise and. The late swing phase demonstrated a very large positive correlation between ST niEMG during the single leg prone hamstring curl, a large positive correlation with the NHE and slider and a moderate positive correlation with the single leg bridge. The remaining correlation coefficients for ST niEMG were small ($0.3 \geq r \geq 0.1$ small).

6.3.9 Gluteus maximus integrated EMG

A very large negative correlation was found between the early stance phase and the slider, and a moderate positive correlation between the single leg Roman chair hold bar exercise. The GM niEMG during the late swing phase showed a large negative correlation with the slider exercise, a moderate positive correlation with the NHE, single leg Roman chair hold body weight and bar exercises and a moderate negative correlation with the single leg bridge. The remaining correlations for GM niEMG were small ($0.3 \geq r \geq 0.1$ small).

6.3.10 Medial gastrocnemius integrated EMG

A large negative correlation was found between the single leg bridge and the early stance phase, and a moderate positive correlation was evident between the single leg Roman chair hold bar exercise. For the late swing phase, moderate positive correlations were observed between the single leg Roman chair hold body weight and bar exercises and a moderate negative correlation between the single leg bridge. All other correlation coefficients for MG niEMG ranged from small to trivial ($0.3 \geq r \geq 0.1$ small; $0.1 \geq r$ trivial).

6.4 Study limitations

The findings and interpretations presented in this study need to be considered in light of the small sample size and the data generated. In particular the spread of the data, as evidenced on the scatter plots for the correlation analyses (Appendices 4 and 5), and the large confidence intervals show a large degree of inter-individual variation was present. Furthermore, the lack of any measurement of sEMG should be considered when interpreting the findings. While some caution is required when interpreting the current findings, the study contributes to current evidence and corroborates with the findings from study two (Chapter 5), prompting the need for further research in the field of HSI prevention.

6.5 Discussion

The aim of this study was to investigate the relationship between the lower limb muscle activation during maximal velocity sprinting and hamstring exercises. In general, there were limited significant relationships for peak activation, and no significant findings observed for niEMG. These findings are a function of the small sample size, and it may be argued that the strength of the relationships is of more relevance rather than statistical significance. For peak activity, the majority of the relationships between the phases of sprinting and exercises revealed positive relationships. Conversely, for the niEMG during the early stance phase and exercises the majority of the relationships for muscle activation were negative, while for the late swing phase, they were positive. The relationships for BFlh activation failed to demonstrate coefficients higher than those that equate to a large correlation, while the ST, MG and GM muscles demonstrated coefficients ranging from very large to almost perfect.

6.5.1 Biceps femoris long head activation

The findings show an overall trend of a positive relationship between BFlh peak and niEMG during the late swing phase and exercises analysed. The BFlh activity during the single leg Roman chair hold exercises demonstrated large positive correlations with the late swing phase of sprinting. The same relationship was evident between the single leg bridge for BFlh niEMG during the late swing phase, however, only a trivial correlation was evident for BFlh peak activity. Both exercises are performed with the knee held isometrically in a position of minimal flexion and thus place the BFlh muscle in an elongated position, similar to that which occurs during the late swing phase of sprinting (Schache *et al.*, 2012; Yu *et al.*, 2008) which may contribute to the current findings. Van Hooren and Bosch (2017b) propose that the hamstrings work in an isometric, rather than eccentric manner during the late swing phase of high-speed running and also suggest that high intensity isometric-based exercise may be equally or possibly even more effective than eccentric exercises for hamstring training. Recent work by Prince and colleagues (2021) also advocates for the potential of isometric exercise as a means of HSI prevention. Consequently, the single leg Roman chair hold and single leg bridge exercises are worthy of further investigation for BFlh activation and training.

In addition to demonstrating a large correlation with the late swing phase in the present study, study two in the current thesis (Chapter 5) showed that the single leg Roman chair hold bar and single leg bridge generated the highest and second highest BFlh peak and niEMG when compared to a series of other exercises. Preferential recruitment of the BFlh muscle has been reported during hip extension-based exercises (Bourne *et al.*, 2017b) and BFlh activity is greatest between knee angles of 15° and 30° (Onishi *et al.*, 2002). During the single leg Roman chair hold exercise the hip remains in a neutral position, however the muscles attempt to extend the hip and preclude extension of the knee joint (Van Hooren and Bosch, 2017b; Macdonald *et al.*, 2018), while the single leg bridge requires the hip to move from neutral to an extended position with knee in minimal flexion. The combination of high muscle activation and long muscle lengths have been reported as key components of strengthening exercises that promote functional and structural adaptations (Bourne *et al.*, 2018a). Therefore, in the context of the findings of study two and three (Chapters 5 and 6), both the single leg Roman chair hold and single leg bridge exercises may be beneficial to target BFlh muscle activation at a long length which may in turn help with the mitigation of injury risk.

There was a trend towards a negative relationship between BFlh activation and the early stance phase. In the majority of cases, BFlh peak activity demonstrated small negative correlations with early stance. However, in comparison to peak activity, larger values for the niEMG for the muscle were observed. In particular, the single leg bridge and single leg Roman chair hold exercises showed moderate, negative relationships with the early stance phase depicting that as muscle activity during early stance decreased a concomitant increase in BFlh activation during the exercises was observed. The negative relationship between sprinting and an exercise demonstrated in this study may be a useful finding as it suggests that those who generate lower levels of hamstring activation during sprinting can achieve higher levels of activation during a given exercise. Furthermore, low BFlh activity in sprinting may suggest that sprinting alone will not condition the muscle sufficiently and that using exercises which only show a positive relationship with sprinting may continue to under-recruit the muscle which may increase the risk of BFlh injury. Therefore, if there are exercises which generate higher BFlh activation relative to early stance then it would appear appropriate to suggest further investigation of these exercises to substantiate their possible role in HSI prevention.

6.5.2 Semitendinosus activation

The majority of the exercises in the current study demonstrated positive relationships for ST peak activity with sprinting. Semitendinosus peak activity during the single leg prone hamstring curl demonstrated a significant, almost perfect positive correlation with the early stance phase. Furthermore, this exercise generated a very large positive correlation for ST peak activity and niEMG with the late swing phase of sprinting. The single leg prone hamstring curl has previously been shown to generate the highest peak and second highest niEMG of the ST muscle when compared to other exercises (Chapter 5) and suggests that the exercise should be considered for ST training. While the single leg Roman chair hold bar exercise only showed a moderate correlation with the late swing phase; this exercise has previously been shown to generate high peak ST activity (Chapter 5) and thus appears worthy of further consideration. Using exercises which bias the ST muscle may contribute to a more balanced response of the synergistic pairing of BF and ST during injury risk situations such as high-speed running (Schuermans *et al.*, 2014). Furthermore, offloading BFlh by targeting the ST muscle may improve hamstring injury prevention and rehabilitation practices (Giakoumis, 2020), which could reduce injury incidence and time-loss.

All the findings observed in relation to ST niEMG during early stance revealed negative relationships with all of the exercises analysed (Table 6.2). This inverse relationship may suggest that the participants generated increased ST activation during the exercises than during the early stance phase and suggests that utilising such exercises to train the ST muscle for sprinting may be beneficial, in particular the single leg bridge and single leg Roman chair hold exercises. In addition to the single leg Roman chair hold bar exercise, the single leg bridge has been shown to generate high ST peak activity and also the highest ST niEMG relative to sprinting when compared to other hamstring exercises (Chapter 5). Consequently, these findings portray the potential value of the single leg Roman chair hold and single leg bridge exercises when considering ST activation and training.

Semitendinosus niEMG during the late swing phase showed positive relationships with all exercises however, the magnitude of the correlation was higher during exercises that required eccentric knee flexion, namely the NHE and the single leg prone hamstring curl. This contrasts with the BFlh niEMG during late swing which demonstrated higher correlation coefficients during isometric based exercises. These findings may be a consequence of the morphology of the BFlh and ST muscles and BFlh being more suited to isometric muscle actions and ST being better able to cope with the strain during eccentric movements (Kubota *et al.*, 2007). An earlier study in the current thesis established the amount of ST niEMG during a range of hamstring exercises and the ST activation was higher during the single leg prone hamstring curl and single leg bridge when compared to the NHE (Chapter 5). Therefore, while a large positive relationship was observed for ST niEMG during the NHE and the late swing phase of sprinting, the amount of ST activation during the single leg bridge as evidenced in an earlier study (Chapter 5), in conjunction with the unilateral nature of the exercise suggests that further investigation of this exercise and its possible contribution to minimising HSI risk is warranted.

6.5.3 Gluteus maximus activation

Gluteus maximus activation during the single leg prone hamstring curl revealed small or trivial correlations with sprinting. This lack of a relationship can be explained by the knee dominant nature of the exercise and depicts a lack of specificity with regards to GM activation during sprinting. Gluteus maximus peak activity demonstrated a very large positive correlation between both phases of sprinting and the single leg bridge exercise, with the correlation between the early stance phase being statistically significant ($p \leq 0.05$). Peak activation of GM during the single leg Roman chair hold bar exercise demonstrated large and moderate relationships with the early stance and late swing phase respectively and the GM niEMG showed a positive, moderate relationship with both sprint phases; a finding which may be reflective of the requirements of the exercise including isometric hip extension and the external load applied. While the relationship of GM peak activation during the single leg

Roman chair hold bar exercise and sprinting was lower than that observed during the single leg bridge, the findings of an earlier study in this thesis showed that the single Roman chair hold exercise generated the highest peak and niEMG of the GM muscle relative to sprinting (Chapter 5). The muscles of the posterior chain play a role in averting hamstring muscle overload during running (Schuermans *et al.*, 2017a) and weakness in the GM muscle is associated with HSI risk (Sugiura *et al.*, 2008). Collectively, the findings of the current study imply that the single leg bridge and single leg Roman chair bar exercise are worthy of further investigation with regards to GM activation and its potential role in addressing HSI risk.

For the majority of exercises the niEMG of the GM muscle was less correlated to sprinting when compared to peak activity. The latter may be a consequence of the nature of the exercises and that the overall amount of GM activity required while performing the exercises is inherently lower when compared to peak activity. The slider exercise contradicts the latter as GM peak activity and niEMG during the exercise was negatively correlated to either a very large or large degree with both the early stance and late swing, as an increase in GM activity was observed during the exercise as it decreased during sprinting (Appendix 5). This finding suggests that those who generate lower levels of GM activation during sprinting achieve a greater degree of activation during the slider, and that the exercise may be beneficial for GM training. To support the latter, an earlier study (Chapter 5), demonstrated that the slider exercise generated relatively high GM activation, thus implying its possible benefits for GM training.

6.5.4 Medial gastrocnemius activation

A previous history of calf injury increases the risk of HSI by up to 50% (Green *et al.*, 2020), thus suggesting that considering gastrocnemius is warranted as it may serve to inform training programmes to decrease HSI risk. The majority of relationships observed for MG activation were positive, however the single leg prone hamstring curl and single leg bridge exercises were negatively correlated to sprinting, thus suggesting that as MG activation increases during the exercise a concomitant decrease occurs during sprinting. In study two of this thesis (Chapter 5) the single leg prone hamstring curl was observed to generate the highest peak activity and niEMG of MG relative to sprinting. However, most of the current findings demonstrate trivial to small relationships between the hamstring curl and sprinting. The latter may be a consequence of the single leg prone hamstring curl being an open kinetic chain exercise and the fact that it does not target or reflect the role of the MG muscle at the ankle during sprinting (Mann and Sprague, 1980). Consequently, when considering the findings of the current research studies, the single leg prone hamstring curl may not be the most beneficial when considering exercises to target MG activation in relation to sprinting.

The single leg bridge generated moderate negative relationships with MG peak activity during both phases of sprinting and the niEMG of the muscle during late swing, and a large negative correlation was observed between the niEMG and early stance phase. During the bridge exercise the knee is held isometrically in a position of minimal flexion which reflects the knee joint position during the early stance and late swing phases of sprinting (Schache *et al.*, 2012) and thus may contribute to the relationships observed. This, in conjunction with findings of an earlier study showing that the exercise generated the third highest peak and second highest niEMG for the MG muscle relative to sprinting (Chapter 5), suggests that the single leg bridge may be of value when targeting MG activation.

Medial gastrocnemius peak activity during the single leg Roman chair hold bar exercise showed a very large positive relationship with the early stance phase and a nearly perfect, positive statistically significant relationship with the late swing phase. The peak activity of the MG muscle during the single leg Roman chair hold body weight exercise demonstrated a moderate positive correlation with the late swing phase while a similar relationship was found for MG niEMG during both phases sprinting. These findings appear encouraging however when considering the findings of the second study in this thesis (Chapter 5), the amount of MG activity generated during the single leg Roman chair hold exercise was relatively low when compared to other exercises. While this exercise and the single leg bridge requires isometric knee flexor contraction in a position of minimal knee flexion, the single leg Roman chair hold exercise is performed in a prone position, requires hip extensor contraction and includes the addition of external load (Macdonald *et al.*, 2018). Collectively, these factors are likely to result in more of a dominant contraction of the hamstrings and thus may explain the relatively low level of MG activity during the single leg Roman chair hold bar exercise when compared to the single leg bridge.

6.6 Conclusion

The current study examined the relationship between muscle activation during the early stance and late swing phases of sprinting and a series of different hamstring strengthening exercises. The findings advocate that further research of the prone hamstring curl, single leg bridge and single leg Roman chair hold would be beneficial to target hamstring muscle activation and to determine their potential role in minimising the risk of HSI. Additional investigation of the single leg bridge and single Roman chair hold bar exercises is further supported when considering the activation of GM and MG and the potential role these muscles play in mitigating HSI risk.

Chapter 7: Prelude

Chapter 6 identified the relationship between lower limb muscle activity during the early stance and swing phases of sprinting and hamstring exercises. While eccentric exercises are an established as part of HSI protocols, the activity of the hamstrings and synergistic muscles and relationships demonstrated in chapter 6 encourage additional research of the prone hamstring curl, single leg bridge and single leg Roman chair hold as part of hamstring training programmes. The data obtained for the studies presented in chapters 4 – 6 was based on a small sample size, therefore, chapter 7 aimed to further establish the findings obtained by using a larger number of participants which required the recruitment of participants from a 15 a-side University rugby team.

In conjunction with exercise choice, the amount of muscle activation requires consideration when developing training protocols. An earlier study in this thesis (chapter 5) demonstrated an increase in muscle activity when load was added to the single leg Roman chair hold exercise. Consequently, using a larger sample size, chapter 7 sought to establish the effect of load on lower limb muscle activity during the prone hamstring curl, single leg bridge and single leg Roman chair hold exercises. The information obtained may enable clinicians to further improve the evidence base regarding hamstring training and the mitigation of injury risk. The sample size in the study detailed in this chapter is higher than in previous chapters however, it is important to recognise that no reliability data are presented for the sEMG metrics included.

Chapter 7

The effect of load on hamstring muscle activity during hamstring strength training exercises

7.1 Introduction

Hamstring strain injuries are one of the most common injuries that occur in sport (Schmitt *et al.*, 2012), particularly in sports that involve high-speed running (Brooks *et al.*, 2006; Ekstrand *et al.*, 2011a). The incidence of HSI and re-injury rates remain high (Ekstrand *et al.*, 2016; van der Horst *et al.*, 2015), suggesting that current prevention and rehabilitation programmes are not effective, and that further research is necessary as a means of optimising training protocols (Vatovec *et al.*, 2020). There is a lack of consensus with regards to the phase of high-speed running in which HSI occurs (Kenneally-Dabrowski *et al.*, 2019a), however knowledge about the injury risk phase and the associated mode of hamstring muscle contraction can be used to inform the specificity and selection of exercises for hamstring training as a means of mitigating HSI risk.

While it is difficult to determine exactly when HSI occurs, some authors report that it usually occurs in the late swing phase of high-speed running during which the hamstrings reach peak length and work eccentrically to decelerate the extending limb (Chumanov *et al.*, 2011; Schache *et al.*, 2012). Consequently, eccentric exercise, in particular the NHE, has been used to modify HSI risk with results of increased hamstring strength and fascicle length being reported (Bourne *et al.*, 2017a; Mjølsnes *et al.*, 2010) and a decrease in injury incidence (Brooks *et al.*, 2006; van de Horst *et al.*, 2015) and recurring HSI being observed (Tyler *et al.*, 2014). Conversely, it has been suggested that isometric hamstring contraction occurs during the late swing phase of high-speed running (van Hooren and Bosch 2017a; van Hooren and Bosch 2017b) and thus isometric exercises require consideration for hamstring training protocols. Recent work demonstrates that the isometric single leg Roman chair hold exercise is superior to the NHE in improving the strength-endurance of the hamstring muscles, and thus may serve as an effective means of lessening HSI risk (Macdonald *et al.*, 2018).

Early research by Garrett and colleagues (1987) suggests that muscle strain injury risk can be reduced by enhancing muscle activity as heightened activation increases the amount of energy absorbed as muscles lengthen. More recently Schuermans *et al.* (2017a) observed decreased trunk and gluteal muscle activation during the late swing phase in soccer players who subsequently incurred a HSI when compared to non-injured counterparts, thus implying that muscle activation contributes to the propensity for the occurrence of injury. Chapter 6 investigated the specificity of hamstring exercises by examining the relationship between muscle activation during sprinting and a series of different hamstring exercises. The findings revealed that hamstring activity during sprinting displayed stronger relationships with exercises that were not eccentrically biased, suggesting that further research is advocated to determine the potential role of the prone hamstring curl, single leg bridge and single leg Roman chair hold exercises in the mitigation of hamstring injury risk.

The nature of HSI is complex with a number of identified risk factors including previous HSI, muscle strength deficits and imbalances and fatigue (Opar *et al.*, 2012). Injury prevention programmes should target associated risk factors thus illustrating that specific muscle strengthening should be incorporated in HSI programmes (Heiderscheit *et al.*, 2010; Malliaropoulos *et al.*, 2012). While a number of studies have investigated muscle activation during different contraction modes of training exercises (Hegyi *et al.*, 2019a; McAllister *et al.*, 2014; Ono *et al.*, 2010) and during hip versus knee biased exercises (Bourne *et al.*, 2017a, 2017b), the effect of external load and loading intensity on muscle activation is reported less frequently (Vatovec *et al.*, 2020; Vigotsky *et al.,* 2015).

Knowledge of the degree of muscle activation during exercises contributes to the development of training programmes (McCurdy *et al.*, 2020). An earlier study in this thesis (chapter 5) demonstrated that the addition of load to the single leg Roman chair hold exercise generated significantly higher BFlh and GM muscle activation. The latter findings corroborate with previous research which report that sEMG is a function of load (Vigotsky *et al.*, 2015; Zebis *et al., 2013).* Increases in muscle activation are implied to be a prediction of improvements in strength (Wright *et al.*, 1999; Vigotsky *et al.*, 2015) as high levels of muscle activity is required to generate muscular adaptations to training exercises (Bourne *et al.*, 2018a).

The clinical relevance and implications of analysing hamstring activation as a function of load is related to the relatively unchanged incidence of HSI rates which has increased over the last two decades and remain high (Ekstrand *et al.*, 2016), thus questioning the effectiveness of current injury prevention strategies and prompting the need for further investigation. The aim of this study was to investigate the effect of load on muscle activation during the prone hamstring curl, single leg Roman chair hold and single leg bridge, which, based on the findings of study three (chapter 6) are exercises that generate high hamstring activity and demonstrate strong relationships with muscle activity during sprinting. The findings could further inform hamstring training programmes and contribute to the development of more informed injury prevention protocols.

7.2 Method

7.2.1 Experimental procedures

Participants were recruited from Cardiff Metropolitan University first 15 a-side rugby team who are Welsh Rugby Union championship players. A sample size of 33 participants was determined for the study via sample size calculations (G*Power software, version 3.1.9.2, Germany) using a significance value of $p \leq 0.05$ and desired power of 0.80. Thirty-five male rugby union players (age: 20.0 ± 1.0 years; height: 1.82 ± 7.7m; mass: 99.0 ± 15.7 kg) were recruited. All players were familiar with resistance training and had been taking part in weight training on a regular basis for at least two years prior to taking part in the study. All participants had to meet the following inclusion criteria: 1) have no history of lower limb injury in the last 12 months; 2) have no history of lower limb surgery; 3) be aged between 18-30 years old; 4) take part in regular training (minimum of 45 minutes x 3 times per week; 5) be injury free and healthy at the time of data collection. This study was approved by the Cardiff School of Sport and Health Sciences Ethics committee (Appendix 6) and all participants were given an information sheet (Appendix 7) and provided written informed consent prior to data collection (Appendix 8). If a participant wished to withdraw from the study at any time, they were asked to complete a withdrawal form (Appendix 9).

All participants completed a Physical Activity Readiness Questionnaire (PAR-Q) (Appendix 10) before taking part – if any participant answered “yes” to any of the PAR-Q questions then they were excluded from the study. Each participant attended the NIAC on two separate occasions and provided written informed consent prior to their first visit. During the first visit participants completed a familiarisation process of the sprinting and exercise protocol and they had the opportunity to practice all exercises; this took place a week before data collection. During their second visit participant height (Seca 213, Seca, Hamburg, Germany) and weight (Seca 7701321004, Seca, Hamburg, Germany) was recorded and then they completed a standardised 20-minute warm-up prior to any data being collected. All participants completed three x 50 m sprints and five repetitions of three different hamstring exercises using three different, progressive loads. Surface electromyography and kinematic data was recorded in the dominant limb, which was defined as the participant's kicking leg (Macdonald *et al.*, 2018; Hegyi *et al.*, 2019a). For specific details regarding the sEMG and kinematic procedures, high-speed running protocol, exercise protocol and data analysis see chapter 3.

7.2.2 Data collection

All participants wore their own trainers, socks, shorts and vests during data collection. Each participant completed the same testing protocol which included a structured warm-up, the placement of sEMG electrodes, three x 50 m sprints, the placement of non-reflective markers and five repetitions of three different hamstring exercises using three different loads. The activity of BFlh, ST, GM and MG of the dominant leg were recorded using a portable sEMG system as per the description in chapter 3.

7.2.3 Exercise protocol

The exercises analysed included the double leg prone hamstring curl, single leg Roman chair hold and single leg bridge and these are described in chapter 3. All exercises were performed in a random order so that there was no biasing of data and to reduce any order of effect due to fatigue. The duration of one repetition varied dependent on each individual exercise, including four seconds for the double leg prone hamstring curl, six seconds for the single leg curl and nine seconds for the single leg Roman chair hold. Five repetitions of each exercise were performed using three progressively greater loads with all trials being video recorded and sEMG and kinematic data being collected synchronously. Two minutes rest was provided between each set of five repetitions and a five-minute rest was provided between each exercise (McAllister *et al.*, 2014; Tsaklis *et al.*, 2015). The loads were calculated as a percentage of the participants body weight and decided based on the requirements of each exercise, including double versus single limb, body position and inclusion of isometric holds per repetition. Additionally, pilot work with a sub-sample of participants was used to determine the upper limit of each load analysed. The external loads for each exercise were as follows:

1) Double leg prone hamstring curl; 20%, 35% and 50% of body weight
2) Single leg Roman chair hold; 10%, 20% and 30% of body weight
3) Single leg bridge; 5%, 15% and 25% of body weight

7.2.4 Surface electromyography normalisation procedures

The sEMG data was quantified via peak activity and iEMG and the mean value of three repetitions (2nd, 3rd and 4th repetition) of each exercise using three different loads. Surface electromyography data were normalised to the highest peak and iEMG which occurred during the first stride in the maximal velocity phase of each participant's fastest high-speed running trial. All data presented in the results and discussion therefore represent normalised values.

7.2.5 Statistical analysis

The sEMG data was analysed using SPSS 27.0 software. A three-way ANOVA with repeated measures (4 x 3 x 3; muscle [BFlh; ST; GM; MG] x exercise [double leg prone hamstring curl; single leg bridge; single leg Roman chair hold]) x load [three different percentages of body weight]) was used to compare the mean differences between the participants that were divided based on three within-subject factors (O'Donoghue, 2012). Before conducting the ANOVA, the assumption of normality was assessed and was deemed to be satisfied as the distribution of data was associated with a skew and kurtosis of less than 2.0 and 9.0 respectively (Schmider *et al.,* 2010). The level of significance was set at $p \leq 0.05$. If sphericity was violated according to Mauchly's test, then the Greenhouse-Geisser adjustment was applied and if a non-significant result was obtained from this adjustment, then the Huynh-Feltd correction was used.

If the ANOVA showed significant interactions or main effects then Bonferroni's *post hoc* analysis was used (Higashihara *et al.*, 2018; McAllister *et al.*, 2014; van den Tillaar *et al.*, 2017). Results are presented as means ± SD and partial eta squared was used to assess the effect sizes of main and interaction effects, using $0.01 < \eta^2 < 0.06$ as a small effect, $0.06 < \eta^2 < 0.14$ as a medium effect and > 0.14 η^2 as a large effect (van den Tillaar *et al.*, 2017). Additionally, the magnitude of difference between variables for the pairwise comparisons was determined via Cohen's *d* effect size statistics. The criteria used were trivial ($d \leq 0.20$), small ($d \leq 0.2$ - 0.49), medium ($d \leq 0.5$ - 0.79) and large ($d \geq 0.80$) effect sizes (Cohen, 1992).

7.3 Results

N = 35 participants were recruited for the study, however, due to some technical and practical difficulties (loosening of the sensor attachment and movement of the sensor resulting in poor signal quality) the data for five participants were removed from the study and thus the final sample for data analyses was n = 30. The mean sprinting speed over 40 m was 7.0 ± 0.59 and participants achieved maximal running velocity between 30 – 40 m.

7.3.1 Normalised peak muscle activity

Table 7.1 shows the nEMG peak activity for all muscles during the exercises analysed. For peak nEMG a significant interaction was observed for load and exercise ($F_{2,116} = 7.07$, $p \leq 0.001$, $\eta^2 = 0.196$) and for exercise and muscle ($F_{6,174} = 7.78$, $p \leq 0.001$, $\eta^2 = 0.212$). There was no significant interaction between load and muscle ($F_{6,174} = 1.71$, $p = 0.121$, $\eta^2 = 0.056$) or load, exercise and muscle ($F_{12,348} = 1.46$, $p = 0.137$, $\eta^2 = 0.048$). Peak activity showed a significant main effect for muscle ($F_{3,87} = 51.15$, $p \leq 0.001$, $\eta^2 = 0.638$) with *post-hoc* analysis indicating significantly higher peak BFlh and ST activity compared to MG and GM ($p \leq 0.001$). A significant main effect was observed for exercise ($F_{2,58} = 16.62$, $p \leq 0.001$, $\eta^2 = 0.359$) and *post-hoc* analysis indicated significantly higher peak activity during the single leg bridge compared to the double leg prone hamstring curl ($p \leq 0.001$) and during the single leg Roman chair hold compared to the double leg prone hamstring curl ($p = 0.006$). Peak nEMG also showed a significant main effect for load ($F_{1,58} = 14.94$, $p = 0.001$, $\eta^2 = 0.340$) and *post-hoc* analysis indicated significantly higher peak activity during load 2 compared to load 1 ($p \leq 0.001$), load 3 compared to load 1 ($p \leq 0.001$) and load 3 compared to load 2 ($p = 0.039$).

Table 7.1 Normalised (%) peak activation (mean ± SD) for lower limb muscles during hamstring exercises using different loads

Exercise	BFlh peak activation	ST peak activation	MG peak activation	GM peak activation
PHC (20% body weight)	53 ± 23	62 ± 31	17 ± 9	15 ± 10
PHC (35% body weight)	69 ± 30	79 ± 36	28 ± 22	17 ± 12
PHC (50% body weight)	82 ± 32	99 ± 46	38 ± 29	22 ± 16
SLB (5% body weight)	89 ± 49	108 ± 49	36 ± 28	43 ± 33
SLB (15% body weight)	86 ± 45	111 ± 52	33 ± 26	52 ± 42
SLB (25% body weight)	92 ± 36	111 ± 50	34 ± 31	44 ± 24
SLRCH (10% body weight)	64 ± 32	75 ± 37	21 ± 17	44 ± 32
SLRCH (20% body weight)	73 ± 32	88 ± 44	29 ± 32	55 ± 56
SLRCH (30% body weight)	80 ± 30	93 ± 40	35 ± 38	57 ± 33

Key: Biceps femoris long head (BFlh); semitendinosus (ST); medial gastrocnemius (MG); gluteus maximus (GM). Prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold (SLRCH)

7.3.2 Within exercise differences

7.3.2.1 Peak activity within different exercises and all loads

Peak hamstring activity was higher in both BFlh and ST than in the MG across all loads during the double leg prone hamstring curl and single leg bridge exercises ($p \leq 0.001$; $d = \geq 0.80$) and the single leg Roman chair (BFlh $p = 0.024$; $d = \geq 0.80$; ST $p \leq 0.001$; $d = \geq 0.80$) (Figure 7.1). A similar pattern of higher hamstring activity for all double leg prone hamstring curl loads was observed when compared to the GM muscle ($p \leq 0.001$; $d = \geq 0.80$), and also for the single leg bridge (load 1 and 3 $p \leq 0.001$; $d = \geq 0.80$; load 2 BF $p = 0.015$; $d = 0.5 - 0.79$; ST $p \leq 0.001$; $d = \geq 0.80$) (Figure 7.1). Semitendinosus activity was higher than GM during the single leg Roman chair hold using all loads (load 1 p ≤ 0.001; $d = \geq 0.80$; load 2 $p = 0.020$; $d = \leq 0.5 - 0.79$ and load 3 p ≤ 0.001; $d = \geq 0.80$), while BFlh activity was only higher than GM using load 1 ($p = 0.024$; $d = \leq 0.5 - 0.79$) and load 3 ($p = 0.012$; $d = \leq 0.5 - 0.79$). Gluteus maximus activity was higher than MG during load 1 of the single leg Roman chair hold exercise ($p = 0.003$; $d = \leq 0.5 - 0.79$) (Figure 7.1). Non-significant differences for within exercise comparisons were found for the BFlh and ST muscles ($d = \leq 0.2 - 0.49$).

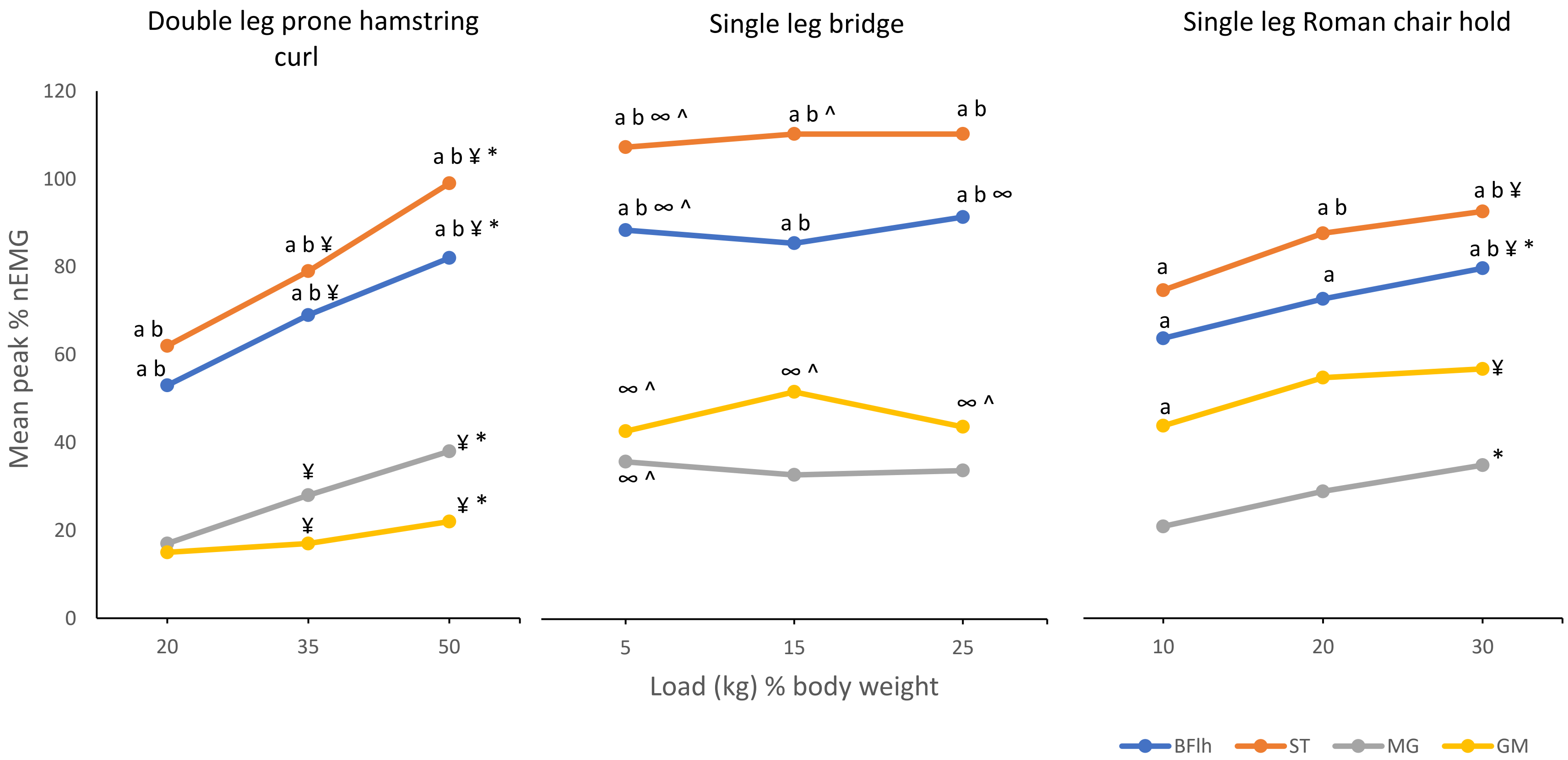

Figure 7.1 Mean peak activity (% nEMG) of Biceps femoris long head (BFlh), semitendinosus (ST), gluteus maximus (GM) and medial gastrocnemius (MG) during the prone hamstring curl (PHC), single leg bridge and single leg Roman chair hold using three different loads. a = significantly different to corresponding MG load; b = significantly different to corresponding GM load. ¥ = significantly different to load one; * = significantly different to load two. ^ = significantly different to corresponding PHC load; ∞ = significantly difference to corresponding SLRCH load

7.3.3 Within muscle differences

7.3.3.1 Peak activity during the double leg prone hamstring curl for all loads

Significance was observed for peak activity during the double leg prone hamstring curl. Hamstring activity increased as the load increased, and both BFlh and ST activity was higher using load 2 compared to 1, load 3 compared to 1 and load 3 compared to 2 ($p \leq 0.001$; $d = \geq 0.80$) (Figure 7.1). A similar pattern was observed for MG activity (load 2 > 1 $p = 0.002$; $d = 0.69$; load 3 > 1 $p \leq 0.001$; $d = \geq 0.80$; load 3 > 2 $p \leq 0.001$; $d = \geq 0.80$) and for GM activity (load 2 > 1 $p \leq 0.001$; $d = \geq 0.80$; load 3 > 1 $p \leq 0.001$; $d = \geq 0.80$; load 3 > 2 $p = 0.001$; $d = 0.74$) (Figure 7.1).

7.3.3.2 Peak activity during the single leg bridge for all loads

Non-significant differences for within muscle differences were observed for all muscles during the single leg bridge exercise across all loads (Figure 7.1). The mean difference between BFlh, ST and MG activity across the different loads during the single leg bridge was trivial ($d = \leq 0.20$) while for the GM muscle a small difference between the means was observed between load 1 and 2 ($d = 0.38$) and load 2 and 3 ($d = 0.21$), and a trivial difference for load 1 and 3 ($d = \leq 0.20$).

7.3.3.2 Peak activity during the single leg Roman chair hold for all loads

Biceps femoris long head activity increased as the load increased, and significance was observed for the difference between activity during load 1 and 3 ($p = 0.002$; $d = 0.69$) and 2 and 3 ($p = 0.003$; $d = 0.68$) of the single leg Roman chair hold exercise (Figure 7.1). Semitendinosus and GM activity was higher during load 3 compared to load 1 (ST $p = 0.035$; $d = 0.49$; GM $p = 0.026$; $d = 0.52$) and for the MG muscle activity was higher during the single leg Roman chair hold using load 3 compared to 2 ($p = 0.022$; $d = 0.52$) (Figure 7.1).

7.3.4 Within load differences

7.3.4.1 Peak activity during load 1 for all exercises

Biceps femoris long head activity during the single leg bridge using load 1 was higher compared to the double leg prone hamstring curl (SLB > PHC $p = 0.006$; $d = 0.62$) and single leg Roman chair hold (SLB > SLRCH $p = 0.039$; $d = 0.48$). A similar pattern was observed for ST activity (SLB > PHC $p \leq 0.001$; $d = \geq 0.80$) and the single leg Roman chair hold (SLB > SLRCH $p \leq 0.001$; $d = 0.74$), and also the MG muscle (SLB > PHC $p = 0.001$; $d = 0.72$; SLB > SLRCH $p = 0.013$; $d = 0.54$). Gluteus maximus activity during the single leg bridge using load 1 was higher compared to the double leg prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) and higher during the single leg Roman chair hold compared to the prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) (Figure 7.1).

7.3.4.2 Peak activity during load 2 for all exercises

No significant differences were observed for BFlh or MG activity using load 2 across all exercises with the difference in means ranging from trivial ($d = \leq 0.20$) to small ($d = \leq 0.2$-0.49). Semitendinosus peak activity was higher during load 2 of the single leg bridge compared to the double leg prone hamstring curl ($p = 0.008$; $d = 0.60$) while GM activity demonstrated a similar pattern to that observed for load 1, with higher activity during the single leg bridge compared to the double leg prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) and during the single leg Roman chair hold compared to the prone hamstring curl ($p = 0.002$; $d = 0.70$) (Figure 7.1).

7.3.4.3 Peak activity during load 3 for all exercises

No significant differences were observed for ST or MG activity using load 3 across all exercises with the difference in means ranging from trivial ($d = \leq 0.20$) to small ($d = \leq 0.2$ - 0.49). Biceps femoris long head activity was higher during the single leg bridge compared to the single leg Roman chair hold ($p = 0.009$; $d = 0.59$), and GM activity was higher during the single leg bridge and single leg roman chair hold when compared to the double leg prone hamstring curl (SLB > PHC $p \leq 0.001$; d = ≥ 0.80; SLRCH > PHC $p \leq 0.001$; d = ≥ 0.80) and higher during the single leg Roman chair hold compared to the single leg bridge exercise ($p = 0.036$; $d = 0.49$) (Figure 7.1).

7.3.5 Normalised integrated EMG

Table 2 shows the niEMG for all muscles during the hamstring exercises analysed. For niEMG a significant interaction was observed for load and exercise ($F_{2,116} = 3.74$, $p = 0.028$, $\eta^2 = 0.114$) and exercise and muscle ($F_{6,174} = 16.68$, $p \leq 0.001$, $\eta^2 = 0.365$). No significant interactions were observed for load and muscle ($F_{6,174} = 1.54$, $p = 0.167$, $\eta^2 = 0.050$) or load, exercise and muscle ($F_{12,348} = 0.84$, $p = 0.606$, $\eta^2 = 0.028$). niEMG showed a significant main effect for muscle ($F_{3,87}$

= 52.69, $p \leq 0.001$, $\eta^2 = 0.645$) with *post-hoc* analysis indicating significantly higher BFlh activation compared to MG ($p \leq 0.001$) and higher ST activity compared to the MG and GM muscles ($p \leq 0.001$). A significant main effect was observed for exercise ($F_{2,58} = 88.20$, $p \leq 0.001$, $\eta^2 = 0.753$) and *post-hoc* analysis indicated significantly higher activation during the single leg bridge compared to the double leg prone hamstring curl ($p \leq 0.001$) and during the single leg Roman chair hold compared to the double leg prone hamstring curl ($p \leq 0.001$). A significant main effect was also observed for load ($F_{1,58} = 8.70$, $p = 0.003$, $\eta^2 = 0.231$) and *post-hoc* analysis indicated significantly higher niEMG during load 2 compared to load 1 ($p = 0.047$), load 3 compared to load 1 ($p = 0.012$) and load 3 compared to load 2 ($p = 0.027$).

Table 7.2 Normalised (%) iEMG (mean ± SD) for lower limb muscles during hamstring exercises using different loads

Exercise	BFlh niEMG	ST niEMG	MG niEMG	GM niEMG
PHC (20% body weight)	287 ± 134	300 ± 154	105 ± 57	73 ± 40
PHC (35% body weight)	337 ± 150	354 ± 185	161 ± 115	84 ± 48
PHC (50% body weight)	411 ± 181	416 ± 195	203 ± 135	106 ± 69
SLB (5% body weight)	840 ± 429	996 ± 473	409 ± 325	286 ± 178
SLB (15% body weight)	817 ± 384	1010 ± 395	390 ± 326	341 ± 241
SLB (25% body weight)	874 ± 332	1040 ± 448	369 ± 309	326 ± 173
SLRCH (10% body weight)	846 ± 366	884 ± 379	309 ± 233	462 ± 283
SLRCH (20% body weight)	920 ± 365	1052 ± 452	397 ± 395	532 ± 373
SLRCH (30% body weight)	1061 ± 415	1147 ± 466	492 ± 492	559 ± 321

Key: Biceps femoris long head (BFlh); semitendinosus (ST); medial gastrocnemius (MG); gluteus maximus (GM). Prone hamstring curl (PHC); single leg bridge (SLB); single leg Roman chair hold (SLRCH)

7.3.6 Within exercise differences

7.3.6.1 Normalised integrated EMG within different exercises and all loads

Hamstring niEMG was higher than MG and GM across all loads during the double leg prone hamstring curl, single leg bridge and single leg Roman chair hold (Figure 7.2) exercises ($p \leq 0.001$; $d = \geq 0.80$). Medial Gastrocnemius activation was higher compared to GM during the double leg prone hamstring curl using load two ($p = 0.016$; $d = 0.60$) and three ($p = 0.015$; $d = 0.60$) (Figure 7.2). Gluteus Maximus activation was higher than the MG muscle during the single leg Roman chair exercise using load one ($p = 0.025$; $d = 0.57$) (Figure 7.2). Non-significant differences for within exercise comparisons were found for the BFlh and ST muscles ($d = \leq 0.2$-0.49).

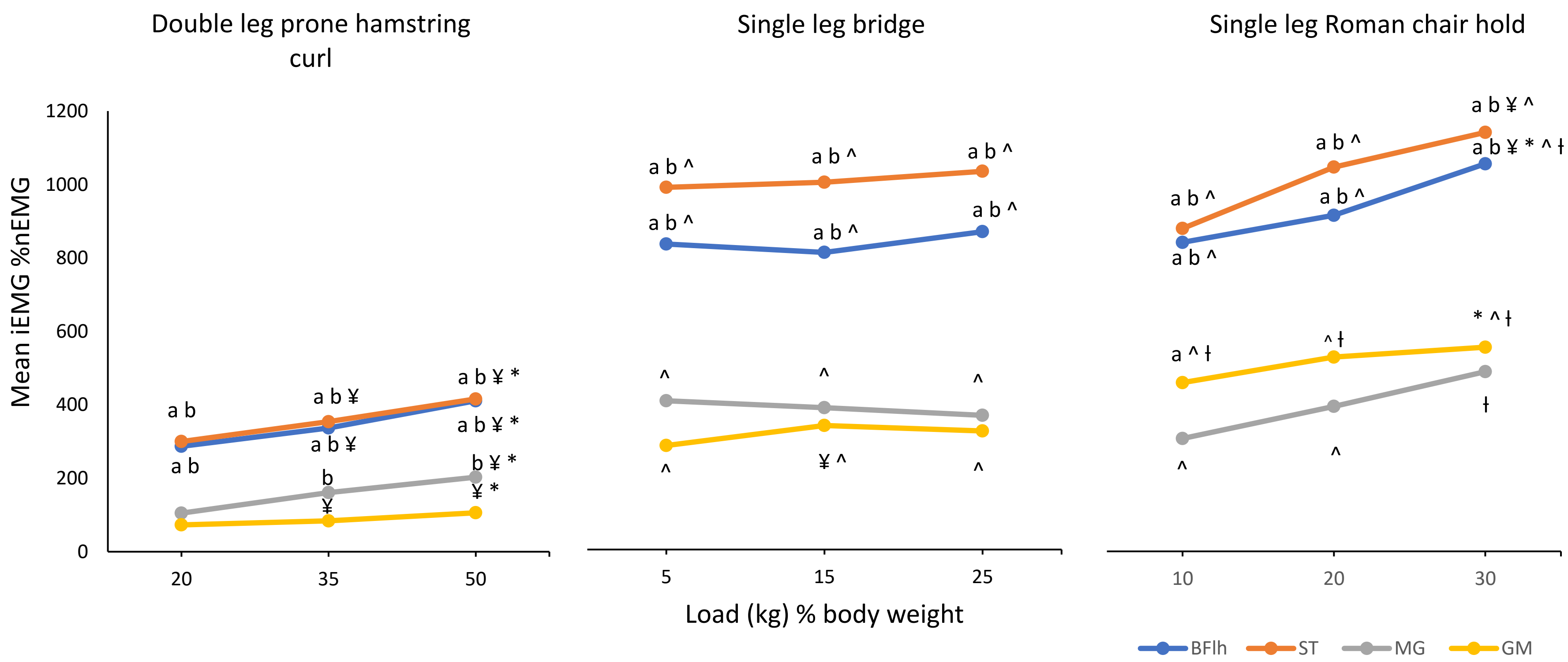

Figure 7.2 Mean iEMG (% niEMG) of Biceps femoris long head (BFlh), semitendinosus (ST), gluteus maximus (GM) and medial gastrocnemius (MG) during the prone hamstring curl (PHC) using three different loads. a = significantly different to corresponding MG load; b = significantly different to corresponding GM load. ¥ = significantly different to load one; * = significantly different to load two. ^ = significantly different to corresponding PHC load; ƚ = significantly difference to corresponding SLB load

7.3.7 Within muscle differences

7.3.7.1 Normalised integrated EMG during the double leg prone hamstring curl for all loads

All muscle activation during the double leg prone hamstring curl was higher during load 2 compared to 1 (BFlh $p \leq 0.001$; $d = 0.72$; ST $p \leq 0.001$; $d = 0.75$; MG $p = 0.005$; $d = 0.64$; GM $p = 0.004$; $d = 0.64$), load 3 compared to 1 ($p \leq 0.001$; $d = \geq 0.80$) and 3 compared to 2 (BFlh $p \leq 0.001$; $d = \geq 0.80$; ST $p \leq 0.001$; $d = > 0.80$; MG $p \leq 0.001$; $d = \geq 0.80$; GM $p = 0.003$; $d = \geq 0.80$) (Figure 7.2).

7.3.7.2 Normalised integrated EMG during the single leg bridge for all loads

No significant differences were observed for BFlh, ST and MG activation as the load changed during the single leg bridge with a trivial ($d = \leq 0.20$) difference between the mean activity being observed. Gluteus maximus activity was higher during single leg bridge load 2 compared to 1 ($p = 0.046$; $d = 0.47$) and a small ($d \leq 0.2$ - 0.49) and trivial ($d = \leq 0.20$) difference between mean activity was observed during loads 1 and 3 and 2 and 3 respectively.

7.3.7.3 Normalised integrated EMG during the single leg Roman chair hold for all loads

Biceps Femoris long head and ST activation was higher during the single leg Roman chair hold using load 3 compared to 1 (BFlh $p = 0.019$; $d = 0.54$; ST $p = 0.004$; $d = 0.65$). Biceps Femoris long head activation was also higher using load 3 compared to 2 ($p \leq 0.001$; $d = \geq 0.80$) (Figure 38) and the same finding was observed for MG activity ($p = 0.012$; $d = 0.57$). No significant differences were observed for the GM muscle and the differences between the means ranged from trivial ($d = \leq 0.20$) to small ($d = \leq 0.2$ - 0.49) (Figure 7.2).

7.3.8 Within load differences

7.3.8.1 Normalised integrated EMG during load 1 for all exercises

All muscles demonstrated higher activation during the single leg bridge and single leg Roman chair hold using load 1 compared to the double leg prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) and GM activation was also higher during the single leg Roman chair hold exercise compared to the single leg bridge ($p \leq 0.001$; $d = 0.77$).

7.3.8.2 Normalised integrated EMG during load 2 for all exercises

Biceps femoris long head, ST and MG activation during the single leg bridge using load 2 was higher compared to the double leg prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) and higher during the single leg roman chair hold compared to the double leg prone hamstring curl exercise ($p \leq 0.001$; BFlh and ST $d = \geq 0.80$; MG $d = 0.72$). A similar pattern was observed for GM activation (SLB > PHC and SLRCH > PHC $p \leq 0.001$; $d = \geq 0.80$) and GM activity was also higher during the single leg roman chair hold exercise compared to the single leg bridge ($p = 0.004$; $d = 0.65$).

7.3.8.3 Normalised integrated EMG during load 3 for all exercises

All muscle activation was higher during the single leg bridge using load 3 when compared to the double leg prone hamstring curl ($p \leq 0.001$; $d = \geq 0.80$) and also during the single leg Roman chair hold compared to the double leg prone hamstring curl exercise ($p \leq 0.001$; BFlh, ST and GM $d = \geq 0.80$; MG $d = 0.76$). Biceps femoris long head, MG and GM activation was also higher during the single leg Roman chair hold exercise compared to the single leg bridge using load 3 (BFlh $p = 0.007$; $d = 0.61$; MG $p = 0.026$; $d = 0.72$; GM $p \leq 0.001$; $d = \geq 0.80$).

7.4 Study limitations

The SD was high across all exercises and loads (Tables 7.1 and 7.2) and therefore needs to be considered when interpreting and discussing the findings. While all participants were from the same rugby squad, suggesting a similar training background and training age, individual differences in strength, positional demands and sprinting style are may influence the muscle activity recorded. The loads used were not matched to a one repetition maximum as is commonly used in other studies (Bourne *et al.*, 2017b; McAllister *et al.*, 2014), however the loads were chosen as a means of replicating what is used clinically and as a result of pilot testing. Finally, the participants included in this study were free from injury, meaning the results may not be directly applicable to injured athletes. Hamstring strain injury results in altered patterns of hamstring activation (Bourne *et al.*, 2016) and architecture (Timmins *et al.*, 2015), and therefore injured and previously injured athletes may respond differently to strength training exercises. Additionally, no measurement of the reliability of the sEMG data was included and requires consideration with regards to the findings presented.

7.5 Discussion

The aim of this study was to investigate the effect of load on muscle activation during exercises which have previously been found to generate high hamstring activity and demonstrate strong relationships with muscle activity during sprinting (chapter 6). All findings for normalised peak activity and iEMG demonstrated a significant interaction ($p \leq 0.001$) and a large effect ($\eta^2 \geq 0.14$) for load and exercise and exercise and muscle. Significance and large effects ($p \leq 0.05$, $\eta^2 \geq 0.14$) were observed for muscle, exercise and load.

A continued increase in muscle activation in response to increased loading was observed during the double leg prone hamstring curl and single leg Roman chair. This finding was significant for all muscles during the double leg prone hamstring curl exercise; however, this was not the case for muscle activation during the single leg Roman chair hold. Loading did not have a significant influence on muscle activation during the single leg bridge, however this exercise generated the highest peak BFlh and ST activity and used the lowest calculated loads relative to body weight. Differences in activation were observed for all muscles using load one across different exercises, however, loads two and three did not generate such a uniform response to muscle activation across exercises. There were no significant differences between the BFlh and ST muscles during any of the exercises and loads investigated, however the findings demonstrated a trend towards greater ST activation across all exercises. Overall, load did not cause a relatively greater increase in hamstring activation compared to MG or GM or vice versa.

Previous work reports that hamstring exercises fail to produce hamstring activity greater than 65% for the ST and 40% for the BFlh of maximal muscle activity that occurs during maximal sprinting on a non-motorised treadmill (van den Tillaar *et al.*, 2017). Similar findings have recently been reported when comparing hamstring activation during isometric, concentric and eccentric based exercises with only 60% of the maximal BFlh and ST activity recorded during over-ground sprinting being generated during the exercises (Prince *et al.*, 2021). These results contrast those observed in the current study with a number of exercises and associated loads generating a minimum of 70% of peak BFlh and ST activity (Table 7.1). The use of body weight exercises in the two aforementioned studies (Prince *et al.*, 2021; van den Tillaar *et al.*, 2017) is a fundamental difference compared to the current study and a contributing factor to the diverse findings observed. In particular, the addition of a progressively greater external load to the double leg prone hamstring curl and single leg Roman chair hold in the current study was key in stimulating higher peak and iEMG.

The primary cause of strain injury is reported to be the amount of strain that the muscle experiences and this may be controlled by muscle activation (Guex and Millet, 2013; Hegyi *et al.*, 2019). Therefore, identifying exercises which maximally activate the hamstrings are likely to better prepare the muscles to cope with the demands of sprinting and thus could contribute to HSI prevention programmes. The next part of this chapter will discuss the findings regarding muscle activation in response to load by presenting each individual exercise accordingly – this approach to the discussion was chosen based on the presentation of findings in the results section.

7.5.1 Double leg prone hamstring curl

The prone hamstring curl exercise is commonly chosen as a means of strengthening the hamstrings (Oliver and Dougherty, 2009). All muscles generated significantly higher normalised peak activity and iEMG with progressive loading with a large mean difference being observed across loads for the BFlh and ST muscles and medium to large mean differences for MG and GM respectively. The double leg prone hamstring curl produced relatively low demands in terms of hamstring activation at lower loads, however BFlh and ST peak activity during load 3 approached similar values to that generated during load 3 of the single leg Roman chair hold exercise.

Semitendinosus peak activity during load 3 of the double leg prone hamstring curl reached 99% relative to sprinting implying that this exercise may be beneficial for ST training. The peak activity and iEMG of the BFlh and ST muscles were significantly higher than the MG and GM muscles. This finding illustrates that while MG activation increased in response to loading, the degree of activity was relatively low suggesting that the hamstrings were likely the main knee flexors contributing to the knee movement during the double leg prone hamstring curl. The low GM activation was an expected finding and this is a consequence of the knee-based nature of the exercise.

There was a trend for higher ST peak activity and iEMG compared to the BFlh during the exercise across all loads, however non-significant differences in activity were observed between the two hamstring muscles. Findings of similar BFlh and ST activation were also observed during a single leg prone hamstring curl using an isokinetic dynamometer in study two of this thesis (chapter 5) and mirrors other work (Zebis *et al.*, 2013). In contrast to these findings, previous studies have reported significantly greater peak activation of ST relative to BF during a prone hamstring curl (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a). The contrasting results may be due to the methodological differences including the background and associated training history of participants which ranged from recreational athletes (Bourne *et al.*, 2017b), amateur athletes (Hegyi *et al.*, 2019a) and high-level athletes in the current study.

The bias of the ST muscle during knee-based exercises has been related to the muscle being better able to tolerate strain during eccentric movements (Kubota *et al.*, 2007) and thus may contribute to relatively higher ST peak and iEMG compared to BFlh during the double leg prone hamstring curl. While progressive loading resulted in greater muscle activity, when compared to the single leg bridge and single leg Roman chair hold, the double leg prone hamstring curl generated relatively low peak and iEMG for both hamstring muscles; a finding which was somewhat expected for the hamstrings due to the knee biased nature of the exercise. Increasing the load further or performing the exercise with a single leg may result in greater hamstring activity, however based on the current findings, the iEMG would need to double as a minimum to approach the levels observed during the single leg bridge and single leg Roman chair hold exercises. The latter suggests that a substantial increase in load would be necessary, which, if tolerated, may restrict how many repetitions could be completed and may also induce alterations in technique as a means of completing the exercise.

During load 3 for the double leg prone hamstring curl and the single leg Roman chair hold, the hamstrings and MG demonstrated similar yet marginally higher peak activity during the hamstring curl exercise. Indeed, ST peak activation reached 99% relative to the maximal velocity phase of sprinting suggesting that the double leg prone hamstring curl would be beneficial for ST training. Acknowledging the load used during these two exercises is relevant here as the external load used during the single leg Roman chair hold was lower than that during the double leg prone hamstring curl (30% vs. 50% body weight) and thus it appears that there would be potential to increase activation if the load of the single leg Roman chair exercise was increased to mirror that used during the prone hamstring curl. Van Hooren and Bosch (2017b) suggest that a large load allowing a maximum of five repetitions should be used for the single leg Roman chair hold and the authors propose a weight of 50% body weight and a three second isometric hold. However, when considering the bilateral versus unilateral nature of these two exercises in conjunction with the addition of an external weight, during the double leg prone hamstring curl each leg was loaded with 25% of body weight during the and thus the loading per limb was higher in the single leg Roman chair hold. This, in conjunction with the difference in repetition duration will contribute to the higher iEMG generated during the single leg Roman chair exercise.

Exercises which generate limited hamstring activation are unlikely to stimulate meaningful adaptations (Hegyi *et al.*, 2019a) therefore the double leg prone hamstring curl may not be the most beneficial exercise for hamstring training. Furthermore, HSI commonly occurs during the early stance (Opar *et al.*, 2015; Orchard, 2012) and late swing phases of sprinting (Schache *et al.*, 2012; 2013; Yu *et al.*, 2008) and during these phases the hamstring muscles resist hip flexion torque in conjunction with knee extension torque. However, during a knee biased exercise such as the prone hamstring curl exercise, the hamstrings are only required to work against the knee joint torque (Van Hooren and Bosch, 2017b), thus implying that other exercises may be more beneficial for hamstring training.

7.5.2 Single leg bridge

During the early stance phase of sprinting muscle activation is high and the hip extension and knee flexion torques are at their maximum (Higashihara *et al.,* 2010a) and during the late swing phase muscle activity is at its highest and the muscle-tendon units are working at their longest length (Chumanov *et al.*, 2012; Schache *et al.*, 2012; 2013; Yu *et al.*, 2008). Consequently, it appears appropriate to encourage the use of exercises which generate high muscle activity and place the hamstrings in a lengthened position for strength development (Bourne *et al.*, 2018a; Schmitt *et al.*, 2012).

Of the three exercises analysed in the current study, the single leg bridge was performed using the lowest calculated loads relative to body weight, yet it was the exercise that generated the highest BFlh and ST activation. The sEMG data demonstrated a bias towards higher ST activation (peak and iEMG) relative to BFlh, however there was no significant difference between hamstring activation and a small mean difference between the BFlh and ST muscles was observed. This finding mirrors previous studies which reported a lack of preferential hamstring peak activity during the single leg bridge (Bourne *et al.*, 2017b; Hegyi *et al.*, 2019a;

Zebis *et al.*, 2013). Loading did not influence peak activity or iEMG, which may suggest that the hamstrings were supra-maximally activated relative to sprinting, even at the lowest load. While both hamstrings generated high activity during the single leg bridge, ST peak activity ranged from 108% - 111% compared to the peak activity during the maximal velocity phase of sprinting, which was considered as 100%; thus, further highlighting the possible benefit of using this exercise for hamstring training. While the BFlh is the most commonly injured hamstring muscle (Koulouris and Connell, 2003; Kenneally-Dabrowski *et al.*, 2019b), it has been suggested that an imbalance between the BFlh and ST influences HSI risk (Schuermans *et al.*, 2016) and therefore addressing the contribution of the ST muscle during hamstring training exercises is warranted.

Findings of chapter 4 in this thesis demonstrated that a body weight single leg bridge generated high peak BFlh and ST activation (88% and 71% nEMG respectively) and it was suggested that the addition of an external load may result in higher muscle activity. While the number of repetitions analysed was higher in the current study, the addition of load did generate higher peak activity. While the loads in the current study used varied across exercises and the exercises themselves present inherent differences, the highest hamstring activation was observed during the single leg bridge which used the lighter externally applied loads. The use of heavy loads is reported to be a prerequisite to enhance muscle unit recruitment and maximise muscular adaptations (Schoenfeld *et al.*, 2014). However, improvements in muscle endurance, strength and hypertrophy have been reported independent of the external load applied (Leger *et al.*, 2011), with some suggesting that lifting lighter loads with a higher repetition number to failure can encourage muscle adaptations similar to training with heavy loads (Burd *et al.*, 2012). Consequently, it appears reasonable to suggest that the single leg bridge could be recommended using minimal load when compared to other exercises, and that manipulating the repetition number may be sufficient for HSI prevention training programmes.

Training the hamstrings in a position that also encourages gluteal muscle activation is warranted as reduced GM activation has a negative effect on HSI risk and incidence (Mendiguchia *et al.,* 2022; Schuermans *et al.,* 2017a; Sugiura *et al.,* 2008). Further the GM muscle may assist the hamstrings in managing the hip flexor torque during sprinting. The single leg bridge generated higher GM activation compared to the double leg prone hamstring curl; an expected finding based on the nature of the curl exercise. While observation of the sEMG data for the GM muscle during the single leg bridge shows a significant increase in peak and iEMG during load two compared to one, overall, the degree of GM activation was relatively low. The latter may illustrate that this muscle made a moderate contribution to the single leg bridge and that the exercise may not provide a sufficient training stimulus for GM and that other exercises require investigation.

The single leg bridge generated a low degree of peak MG activity however the iEMG reached modest levels. Overall, the data demonstrates that the addition of load did not generate any meaningful increase in activation and that the magnitude of peak activity was relatively low across all loads. As the lowest load stimulated the highest level of MG peak activity and iEMG it may be reasonable to suggest that using this load would allow the completion of more repetitions and enable the most optimal contribution of the MG muscle to the exercise.

7.5.3 Single leg Roman chair hold

A continued increase in peak activity and iEMG was observed across all muscles as loads increased during the single leg Roman chair hold exercise. Observation of the results show that a modest magnitude of peak activity was generated for both the BFlh and ST, however high levels of iEMG were observed. Therefore, while this may suggest that the exercise was not as effective as the single leg bridge in stimulating high levels of peak activity, the overall amount of activity throughout the exercise remains high indicating that the single leg Roman chair hold may be an appropriate exercise if the goal is to generate high levels of iEMG.

The ST muscle generated non-significant higher activation compared to the BFlh with a small mean difference being observed. These findings differ to an earlier study in this thesis (chapter 5) which demonstrated higher BFlh activity relative to the ST muscle during the single leg Roman chair hold using body weight and a 20kg load. Furthermore, compared to the maximum activity during sprinting, BFlh peak activation was 123% which was the highest level of activation observed for this muscle compared to the other exercises analysed (chapter 5). The difference in BFlh and ST activation between both studies may be attributed to the training background of the participants. The single leg Roman chair hold was incorporated in the training programme of the sevens rugby players (chapter 5) while the current participants were not familiar with the exercise, therefore as the BFlh muscle is better suited to isometric muscle actions (Kubota *et al.*, 2007) the regular use of the exercise may contribute to the observed differences in BFlh and ST activation. Additionally, the NHE is a regular part of the training programme for the current participants in this chapter and therefore the relatively higher ST activation observed compared to the BFlh muscle may be the consequence of using exercises that selectively target the ST muscle (Bourne *et al.*, 2017b; Mendiguchia *et al.*, 2013b).

In comparison to isotonic muscle contractions, isometric actions generate a greater fatiguing stimulus (Kay *et al.*, 2000) and muscle activity may increase during individual sets of repetitions and also across sets as a means of overcoming fatigue (Smilos *et al.*, 2012). The latter may contribute to the high hamstring iEMG observed when compared to the peak activity, as the amount of hamstring work may have increased as the exercise progressed. Consequently, it appears appropriate to suggest that the single leg Roman chair hold may be a beneficial exercise to improve muscle endurance which is an identified as a risk factor for HSI (Freckleton *et al.*, 2014; Schuermans *et al.*, 2016). The latter has been confirmed by recent work by MacDonald and colleagues (2018) demonstrating that the single leg Roman chair hold exercise greatly improved hamstring muscle endurance when compared to the NHE.

The muscles of the posterior chain function to impede overload of the hamstrings during running (Schuermans *et al.*, 2017a), therefore exercises which encourage high GM activation are worthy of attention when focussing on HSI prevention programmes. The single leg Roman chair hold generated the highest GM peak and iEMG compared to the other two exercises across all loads, however the magnitude of activation only reached modest levels. Gluteus maximus peak activity was similar to that observed during the single leg bridge with trivial mean differences being observed between loads one and two, however activity was significantly higher during load three of the single leg Roman chair hold compared to the single leg bridge. The iEMG of the GM muscle was significantly higher during the single leg Roman chair hold compared to the single leg bridge across all loads. The longer repetition duration of the single leg Roman chair hold (nine seconds) compared to the single leg bridge (six seconds) will contribute to the findings of iEMG as it represents the amount of electrical potential required to complete the movement and is time dependant (Vigostsky *et al.*, 2015). The latter will also contribute to the iEMG findings for the MG which were similar to, yet marginally higher than those during the single leg bridge exercise. While the iEMG was relatively high, the peak MG activity was low during the single leg Roman chair hold with values being similar to those observed during the double leg prone hamstring curl and indicating that alternative exercises would need to be explored to stimulate the MG sufficiently to achieve a training effect.

During the single leg Roman chair hold exercise the hip and knee joints are held in positions of minimal flexion and thus there is no change in the moment arm of the load through the knee and hip joint. It has been argued that muscle fibres act in an isometric manner during the swing phase of high-speed running and therefore isometric rather than eccentric exercise may be more effective for hamstring training (Van Hooren and Bosch, 2017a; 2018). This, in conjunction with the high hamstring and moderate GM activation observed portrays the single leg Roman chair hold as a beneficial for HSI prevention programmes. While it is not possible to conclude that higher muscle activation stimulates superior adaptations to training (Macdonald *et al.*, 2018), as a result of the current findings, the addition of further load, increasing the duration of isometric hold or a combination of both factors, may stimulate higher hamstring activation and be of benefit for hamstring training. Loads of 50% body weight have previously been recommended for the single leg Roman chair hold (Van Hooren and Bosch, 2017b) and 10 second holds per repetition have been used as part of a training study (Macdonald *et al.*, 2018), and thus could be further investigated to determine the role of this exercise in HSI prevention programmes.

7.6 Conclusion

Strength deficits have been identified as a risk factor for HSI and while it is not possible to definitively conclude that increases in muscle activation will result in strength improvements, it appears reasonable to suggest that exercises which generate high levels of hamstring activity will be beneficial for mitigating injury risk. The findings of this study show that progressive loading generated a continued increased in muscle activation during the double leg prone hamstring curl and single leg Roman chair hold exercises. Collectively however, while loading did not influence the magnitude of activation, the single leg bridge, even with low levels of loading, generated the highest hamstring muscle activity. The ease of administering the single leg bridge, in the absence of heavy, specialist equipment, portrays the exercise as an attractive option for hamstring training programmes.

The single leg Roman chair hold generated moderate levels of peak hamstring activity, however, high levels of iEMG were observed. Increasing activity further may be possible with higher loading. However, this would likely require some investment of time to progress the athletes to a position where they competently perform the exercise with the higher degree of loading. High BFlh activity was observed in this study, however it was lower than that observed in the ST muscle as all exercises generated the highest level of activity in the medial hamstring. Furthermore, in contrast to the findings for ST, BFlh peak activity did not reach the values reached in sprinting. Consequently, additional research is warranted to further explore exercises which generate the highest levels of BF peak activity.

While the findings of this study have outlined the effect of load on muscle activation during three different hamstring exercises, patterns of muscle activity alone do not provide sufficient evidence for the effectiveness of individual exercises as an HSI prevention tool. Therefore, future research investigating the effects of training exercises, specifically the single leg bridge and single leg Roman chair hold, on the possible mitigation of injury risk and HSI incidence appears warranted.

Chapter 8

Discussion

8.1 Research limitations

Collectively, the findings of this thesis draw attention to the impact of exercise selection on hamstring activation. However, prior to discussing the main findings and their implications, it is important to acknowledge some limitations of the research to help inform and develop future practice – these limitations are identified below:

- Surface electromyography data can be variable and while the reliability of sEMG measurements for lower limb muscles has previously been reported (Bussey *et al.,* 2018; Fauth *et al.,* 2010; Smoliga *et al.,* 2010; Suydam *et al.,* 2017), no measurement of sEMG reliability was completed as part of this thesis.
- Electrodes were attached to a single site per muscle group for data collection in the current thesis, however this method does not enable regional activity throughout the length of individual muscles. Two electrodes could have been placed on two sites of each muscle to record activity, however recent work by Hegyi and colleagues (2019a) demonstrates that hamstring activity during training exercises is not uniform throughout the length of the muscle, advocating the use of high-density EMG to provide a more representative mean of muscle activity. The relevance of the latter links to the lack of consensus regarding the location of injury within the hamstring muscle (Askling *et al.*, 2007; De Smet and Best, 2000; Koulouris *et al.*, 2007). While acknowledging the benefit of high-density EMG, using a single location on a muscle continues to be used as an established method of measuring muscle activity for research purposes (Bourne *et al.*, 2017a; Ono *et al.*, 2010; McManus *et al.,* 2020; van den Tillaar *et al.*, 2017).
- Sprinting-based sports are the main cause of HSI therefore, the aim of this thesis was to investigate hamstring muscle activation during sprinting and strength training exercises in an attempt to add to the specificity of hamstring training and injury prevention strategies. However, HSI is multi-factorial in nature and thus investigating muscle activity in isolation may be viewed as a limitation as it does not consider all of the demands that the hamstrings experience during sprinting, such as muscle strain

and force. While a given exercise may generate lower activation, the degree of strain may be higher and thus may provide suitable mechanical stress to simulate adaptation.

- The findings of chapters 4-6 are based on a limited sample size. The available sample was limited as participants were international rugby sevens players, which in conjunction with some of the sEMG data being unavailable for analysis, means the results are specific to the participants involved, and thus confidence may be low when attempting to generalise to a wider population. However, the research is in line with the small, similar sample sizes which have been used in other sEMG studies (Ono *et al.*, 2010; 2011; Schache *et al.*, 2013). Chapter 7 addressed this issue by collecting data using a larger sample that was based on a power calculation and a larger available group of participants, which provided a sample size in excess of most published sEMG based studies in HSI literature.
- The results presented in this thesis are based on data collected from high-level rugby players, therefore the findings may not be generalisable to those playing rugby at lower levels of competition or to other sporting populations. Furthermore, the participants recruited for this thesis were injury free and thus different findings may be obtained in the presence of hamstring injury and / or during the period of rehabilitation.
- The findings of this thesis demonstrate the muscle activation patterns during common hamstring training exercises and the acute effect of load on muscle activation. However further research is needed to determine the longer, more chronic effect of loading and to further identify exercises which are most beneficial at minimising HSI risk.

8.2 Overview

The aim of this thesis was to examine the activity of the hamstrings and synergistic muscles during the early stance and late swing phases of maximal velocity sprinting and hamstring strength training exercises in high-level rugby union players. The outcomes of the body of work in this thesis furthers the knowledge and understanding of hamstring activation during commonly employed exercises relative to sprinting. The findings provide practitioners with information regarding exercise selection to target the BFlh and ST muscles and draws attention to the influence of load on muscle activation, which may influence adaptations to training and mitigation of injury risk.

Investigation of the GM and MG muscles was included in this thesis because of the synergistic role that these muscles play with the hamstrings at the hip and knee respectively. Further, GM weakness and reduced activation has been reported to influence hamstring loading and injury risk (Schuermans *et al.*, 2017a; Sugiara *et al.*, 2008) and a history of calf injury increases the risk of HSI (Green *et al.*, 2020). The studies presented in chapters 4-7 discuss the contribution of the GM and MG muscles and demonstrated that their activation was generally only low to moderate during the exercises analysed. Therefore, this chapter will focus specifically on BFlh and ST to identify the key results and how these may benefit or influence practical applications in the field.

In Chapter 1 of this thesis a series of objectives were outlined and these were researched in the studies detailed in Chapters 4-7. The next part of this chapter will identify the key findings of the research related to each objective.

Objective 1: *Analyse and compare lower limb muscle activity during the early stance and late swing phases of the maximal velocity phase of sprinting.*

There is a lack of consensus as to when HSI occurs during sprinting, however the early stance (Ono *et al.*, 2015; Orchard, 2012) and late swing phases (Chumanov *et al.*, 2012; Schache *et al.*, 2012; 2013) and the transition between the two phases (Liu *et al.*, 2017) are proposed as the periods during which HSI commonly occurs. Consequently, chapter 4 aimed to examine hamstring activation during the different phases of the sprinting gait cycle.

- Peak BFlh activity reached the same level in both the early stance and late swing phases, while the highest ST peak activity was generated in late swing.
- Peak BFlh activity was higher relative to ST during early stance and late swing.
- The relative difference between BFlh and ST activation varied depending on the phase of the sprint. Biceps femoris long head peak activity was higher than ST during early stance and late swing. A large ($d \geq 0.80$) mean difference was observed between peak activity of BFlh and ST during early stance, while a small difference was evident between the hamstrings during the late swing phase ($d \leq 0.2$ - 0.49).

- Significantly higher BFlh and ST iEMG was observed during the late swing phase compared to early stance. A large ($d \geq 0.80$) mean difference was observed between BFlh iEMG during late swing and early stance and a medium ($d \leq 0.5$-0.79) difference for ST iEMG during both phases of sprinting.
- The greater iEMG of BFlh during late swing and peak activity in early stance relative to ST may contribute to the propensity of the BFlh muscle to injury.

Objective 2: *Examine lower limb muscle activity during hamstring strength training exercises.*

Hamstring strain injury is multi-factorial with identified modifiable risk factors including decreased muscle strength (Schuermans *et al.*, 2016; Timmins *et al.*, 2016a) and altered neuromuscular control (Schuermans *et al.*, 2014). The degree of strain experienced by muscle is the primary cause of strain injury and may be controlled by muscle activation (Hegyi *et al.*, 2019a), therefore, knowledge regarding muscle activation during hamstring exercises is relevant as it may serve to improve exercise prescription for injury prevention programmes. Consequently, the aim of chapter 5 was to examine lower limb muscle activity during hamstring strength training exercises.

- Hamstring activation was greater during exercises that were not eccentrically biased.
- Intermuscular hamstring activity did not show any significant differences; however, the results identified a trend towards higher BFlh activation across all exercises.
- Biceps femoris long head activation was at its greatest during the single leg Roman chair hold 20kg bar exercise which requires isometric contraction of the muscle at the hip and knee at long muscle lengths. Peak BFlh activity during this exercise exceeded the 100% reference value of sprinting. This novel finding suggests that this exercise could be beneficial for hamstring training.
- The pattern of ST activity was different to BFlh as the highest peak and iEMG were generated during different exercises. The highest peak activity occurred during the single leg prone hamstring curl and the greatest iEMG during the single leg bridge.
- Collectively, the findings characterise the BFlh and ST muscle activation patterns during hamstring strength training exercises. Practitioners wishing to target BFlh and ST activation should consider the single leg Roman chair hold, single leg bridge and single leg prone hamstring curl exercises.

Objective 3: Examine the association between lower limb muscle activation during the early stance and late swing phases of the maximal velocity phase of sprinting and hamstring strength training exercises.

Knowledge of muscle activation patterns during hamstring strength training exercises serve to aid practitioners with exercise prescription. However, in addition to understanding hamstring activation during various exercises, the specificity of training programmes could be improved by comparing the hamstring activity during exercise to that which occurs during sprinting. Thus, the aim of chapter 6 was to examine the association between hamstring muscle activation during sprinting and different strength training exercises.

- Biceps femoris long head activation during the late swing phase of sprinting demonstrated positive relationships with the exercises analysed. In particular, the isometric based single leg Roman chair hold exercises generated normalised peak and iEMG of BFlh that demonstrated large positive correlations with the late swing phase. The niEMG of BFlh during the single leg bridge showed the same relationship.
- Conversely, BFlh activity during the early stance phase demonstrated a trend towards negative relationships with the exercises. A key finding was that moderate negative relationships were observed between BFlh niEMG during early stance and the single leg Roman chair hold exercises and single leg bridge. This finding may be of clinical significance as it suggests that sprinting alone may not be sufficient to train BFlh in those who generate lower levels of activity. Further, exercises which achieve greater muscle activation relative to the early stance phase of sprinting are likely to be beneficial to support hamstring training.
- A significant, almost perfect correlation was observed for ST peak activity during early stance and the single leg prone hamstring curl. Furthermore, this exercise demonstrated a very large positive correlation for ST peak activity and iEMG with the late swing phase of sprinting.
- A pertinent finding was that niEMG of the ST muscle during early stance demonstrated a negative relationship with all exercises, with the single leg bridge and single leg Roman chair hold exercises showing very large and large negative correlations respectively.

- In contrast to the early stance phase, the ST niEMG during late swing demonstrated positive relationships with all exercises. A further finding was that the magnitude of the relationship was higher during exercises involving eccentric knee flexion, suggesting that this be considered by practitioners when selecting exercises to stimulate ST activation.

Objective 4: *Establish the effect of load on lower limb muscle activity during hamstring strength training exercises.*

High activation and long lengths of the BFlh and ST muscles occur during the early stance and late swing phases of running (Schache *et al.*, 2013), thus exercises which simulate these elements may be beneficial to prepare the hamstrings for the demands of sprinting and address the mitigation of HSI risk. The findings of chapters 5 and 6 demonstrated that the single leg Roman chair hold, single leg bridge and single leg prone hamstring curl generated high hamstring activation and that the activity during these exercises showed strong relationships with hamstring activity during sprinting. High degrees of muscle activation are necessary to produce muscular adaptations to training exercises (Bourne *et al.*, 2018b) and the sEMG of an agonist muscle is a function of load (Vigotsky *et al.*, 2015). Therefore, the aim of chapter 7 was to establish the effect of load on hamstring muscle activity during hamstring strength training exercises.

- Several exercises and the associated loads generated a minimum of 70% of peak BFlh and ST activity which suggests that they may encourage positive adaptations if used for hamstring training.
- At a given load, no significant differences in hamstring activity were reported, however, a trend towards higher ST activation was observed during all exercises.
- The effect of load on muscle activity varied across exercises. Significant increases in the activation of all muscles were observed during the double leg prone hamstring curl exercise. Incremental loading of the single leg Roman chair hold exercise also resulted in a continued increase in muscle activation, however this finding did not reach significance.

- The single leg bridge was performed using the lowest loads relative to body weight yet resulted in the highest BFlh and ST peak activity, however loading did not have a significant impact on the level of activation. Also, the single leg bridge generated ST activity that exceeded the 100% reference value of sprinting implying the benefit of this exercise for ST training.
- The double leg prone hamstring curl produced relatively low demands in terms of hamstring activation at lower loads, however higher activity was generated with the highest load. Semitendinosus peak activity using the highest load generated 99% peak activity relative to sprinting, illustrating that this exercise could be beneficial for ST training.
- The overall amount of hamstring activity during the single leg Roman chair hold illustrates that this exercise would be an appropriate choice if generating high levels of iEMG, such as targeting muscle endurance is a goal of training programmes.
- The results of chapter 7 advocate that practitioners should consider using the single leg bridge and single leg Roman chair hold for BFlh and ST training as a means of addressing HSI risk.

8.3 Clinical perspective and practical recommendations

Sports which include repetitive sprinting cause a high incidence of HSI and also demonstrate a high rate of re-injury (Brooks *et al.*, 2006; Ekstrand *et al.*, 2016), therefore consideration of hamstring muscle activity during sprinting and commonly used strength training exercises is warranted as a means to improve injury prevention practices. Chapters 5 and 7 demonstrated that several exercises generated a minimum of 70% of peak BFlh and ST activity relative to sprinting. In particular, BFlh activity during the single leg Roman chair hold 20kg bar (chapter 5) and ST activity during the single leg bridge (chapter 7) exceeded the 100% reference value of sprinting. This novel finding contrasts with previous studies which conclude that strengthening exercises targeting the hamstrings, including a single leg bridge and the NHE fail to generate muscle activity which resembles those produced during sprinting (Prince *et al.*, 2021; van den Tillaar *et al.*, 2017).

The use of eccentric exercise to decrease HSI incidence (Brooks *et al.*, 2006; Petersen *et al.*, 2011) and as part of rehabilitation has been previously established (Askling *et al.*, 2013; 2014).

However, the findings from chapter 5 show that the relative activity of the BFlh and ST muscles during the NHE and slider did not stimulate the hamstring muscles to the same degree as other exercises, thus illustrating the potential benefit of using exercises that are not eccentrically biased to generate high hamstring activation. Exercises which generate higher muscle activity may have greater potential to stimulate adaptations to training compared to those which produce relatively lower activation and therefore the findings of this thesis have clinical implications. In particular, the isometric based single leg bridge and single leg Roman chair hold exercises and the single leg prone hamstring curl were found to generate high hamstring activity, and further analysis showed that this activity demonstrated strong relationships with that observed during the early stance and late swing phases of sprinting.

Additional examination of the isometric exercises and a double leg prone hamstring curl showed that progressive loading influenced muscle activation to a greater degree during the prone curl and single leg Roman chair hold exercises compared to the single leg bridge. Of note here is the difference between the prone hamstring curl exercises analysed in chapter 5 and 7. In chapter 5, a single leg prone hamstring curl was performed on an isokinetic dynamometer as this was typically used by the participants included in the study. However, in chapter 7 a double leg prone hamstring curl using a more traditional curl machine was included in the exercise protocol as it was felt this exercise better represented what is more routinely used and prescribed in the clinical environment. When considering all of the exercises analysed, the double leg prone hamstring curl generated the lowest activation and thus may not be the most beneficial exercise for hamstring training. Furthermore, a knee-based exercise will not target the hip flexion torque that the hamstrings must oppose during sprinting, thus other exercises may be of greater value for hamstring training.

Chapter 7 presented an interesting finding as the single leg bridge was the exercise that generated the highest peak hamstring activity, even though the loads used were the lowest relative to body weight. While there were no significant differences in hamstring activity as during progressive loading of the single leg Roman chair hold exercise, significantly higher hamstring activity was observed during load 1 of the single leg bridge compared to the corresponding load of the single leg Roman chair hold. Furthermore, load 3 of the bridge exercise generated significantly higher BFlh activity compared to load 3 of the single leg

Roman chair hold. The single leg bridge also produced high iEMG of the hamstring muscles, which in conjunction with the findings of peak activity and the hip and knee joint angles which are similar to those important for high-speed running (Askling *et al.*, 2007; Heidsercheit *et al.*, 2010) implies the benefit of using this exercise for hamstring training. Furthermore, the low loads administered to generate the level of activation observed makes the exercise easy to administer and increases the practicality of its use as it requires minimal equipment.

All of the conclusions and recommendations of this thesis are based on outcomes from research using group-based analyses, however, it is important to note that not all individuals will follow the group response. The large SDs presented in chapters 5, 6 and 7 show the degree of inter-individual variability of the data and while some exercises resulted in peak activity that exceeded 100% of the sprint data, not all individuals will generate this degree of activation. Based on the findings of this thesis, practitioners should acknowledge the potential for inter-individual variability in muscle activation, and it may be appropriate to suggest that individuals are screened to determine the patterns of muscle activity to aid exercise prescription. While the latter identifies the ideal scenario, it would be time consuming and inaccessible to many practitioners to screen muscle activation patterns and thus such an approach may not be feasible in practical settings. Hence this thesis has sort to presented clinical recommendations that can be provided based on the current best levels of evidence available.

8.4 Directions for future research

While the findings of this thesis contribute to the knowledge regarding hamstring activation during strength training exercises and the effect of load on muscle activation relative to sprinting, further research is needed to increase our understanding of hamstring activity during exercises as a means to better inform injury prevention strategies.

- Using high density EMG to analyse region dependent muscle activity during sprinting and the exercises identified in this thesis would be beneficial. The findings would help to gain further insight and clarify the clinical relevance of proximal to distal regional differences in hamstring activation and would further add to the findings of this thesis and contribute to the specificity of hamstring muscle training and injury prevention programmes.

- During the clinically relevant late swing phase of sprinting, the hamstring MTU generate high forces and reach their peak length (Chumanov *et al.*, 2007a; Van Hooren and Bosch, 2017a). Therefore, in addition to examining regional differences in activation during strength training exercises, measuring muscle forces would be beneficial as exercises which generate large forces are likely to be superior at increasing muscle strength (Collings *et al.,* 2023; Van Hooren *et al.*, 2022).
- Investigation of the findings of this thesis using different populations would further confirm the potential of the exercises identified for hamstring training.
- The results of chapter 7 show the acute effects of loading on three exercises which demonstrated strong relationships with sprinting (chapter 6). A longitudinal study to investigate the effects of the exercises on strength, strength-endurance and HSI incidence would be beneficial to further determine the role of these exercises in modifying the injury risk related to sprinting.

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APPENDIX 1 ETHICS FORM (STUDIES 1-3)

When undertaking a research or enterprise project, Cardiff Met staff and students are obliged to complete this form in order that the ethics implications of that project may be considered.

If the project requires ethics approval from an external agency such as the NHS or MoD, you will not need to seek additional ethics approval from Cardiff Met. You should however complete Part One of this form and attach a copy of your NHS application in order that your School is aware of the project.

The document ***Guidelines for obtaining ethics approval*** will help you complete this form. It is available from the Cardiff Met website.

Once you have completed the form, sign the declaration and forward to your School Research Ethics Committee.

PLEASE NOTE:
Participant recruitment or data collection must not commence until ethics approval has been obtained.

PART ONE

Name of applicant:	Adeline Phillips
Supervisor (if student project):	Dr Craig Ranson
School:	School of Sport
Student number (if applicable):	20075616
Programme enrolled on (if applicable):	PhD
Project Title:	Hamstring Function During Elite Sprint Running and Strengthening Exercises
Expected Start Date:	01/05/2015
Approximate Duration:	4 years
Funding Body (if applicable):	Click here to enter text.
Other researcher(s) working on the project:	Dr Isabel Moore Dr John Oliver Dr Ian Bezodis
Will the study involve NHS patients or staff?	No
Will the study involve taking samples of human origin from participants?	No

In no more than 150 words, give a non-technical summary of the project
Hamstring strains are the most common muscle injury in sport (Mendiguicha *et al.*, 2012) and account for between six and 29% of all injuries reported in Australian Rules Football, Rugby Union, Soccer, Cricket and track sprinters (Brooks *et al.,* 2006; Woods *et al.*, 2004) with high-speed running being the most common activity at time of injury (Woods *et al.*, 2004; Brooks *et al.*, 2006). However, the exact mechanism of injury is unknown (Chumanov *et al.*, 2012) and although strength training has been shown to be preventative the re-injury rate remains high (Crosier, 2004; Malliaropoulos *et al.*, 2011). The aim of this project is to analyse the magnitude and timing of hamstring muscle action during sprinting and to compare this to a series of traditional and novel hamstring training exercises. The effects of training using exercises that seem to be most appropriately matched to the measured function of hamstrings during sprinting will then be investigated.

Does your project fall entirely within one of the following categories:	
Paper based, involving only documents in the public domain	No
Laboratory based, not involving human participants or human tissue samples	No
Practice based not involving human participants (eg curatorial, practice audit)	No
Compulsory projects in professional practice (eg Initial Teacher Education)	No
If you have answered YES to any of these questions, no further information regarding your project is required. If you have answered NO to all of these questions, you must complete Part 2 of this form	

DECLARATION: **I confirm that this project conforms with the Cardiff Met Research Governance Framework**	
Signature of the applicant: A J Phillips	Date: 15th January 2015
FOR STUDENT PROJECTS ONLY	
Name of supervisor: Dr Craig Ranson	Date: 15th January 2015
Signature of supervisor: 	

Research Ethics Committee use only	
Decision reached:	Project approved ☑ Project approved in principle ☐ Decision deferred ☐ Project not approved ☐ Project rejected ☐
Project reference number: 15/1/03R	
Name: Dr. Brendan Cropley	Date: 26/01/2015
Signature: 	
Details of any conditions upon which approval is dependant: Click here to enter text.	

PART TWO

A RESEARCH DESIGN	
A1 Will you be using an approved protocol in your project?	No
A2 If yes, please state the name and code of the approved protocol to be used[1]	
Click here to enter text.	
A3 Describe the research design to be used in your project	

Sample and sampling

Participants for the proposed study will be 18–30-year-old rugby players playing a minimum of university team level, training or playing for an average of at least 45 minutes, twice a week. A Rugby team will be chosen and the coach will be approached to gain consent to speak to the players and give them all the opportunity to participate in the study. Twenty participants will be recruited.

Recruitment of participants

Following initial discussions with the rugby coach and players, a letter explaining the procedures and scope of the study will sent to the participants (Appendix 1) and accompanying letters of informed consent (Appendix 2) will be distributed to all those participating in the study.

Data Collection

All data collection will take place in the National Indoor Athletics Centre (NIAC) at the School of Sport, Cardiff Metropolitan University. Prior to data collection each participant will have read the information sheet and will have provided written informed consent. All participants will complete a familiarisation process prior to data collection – this will take place at each visit. The sprinting trials and hamstring training exercises will be explained and each participant will have the opportunity to practice them. Each participant will

[1] An Approved Protocol is one which has been approved by Cardiff Met to be used under supervision of designated members of staff; a list of approved protocols can be found on the Cardiff Met website here

need to attend NIAC on two separate occasions, with a 48-hour interval between each visit. Each participant will complete a standardised 15-minute warm-up during each visit prior to any data being collected.

Study outline

Visit 1 - the first aim of this study is to evaluate the magnitude and timing of hamstring activity through the sprinting cycle. The results will inform the identification of suitable hamstring training exercises. Data will be collected from six muscles using a wireless electromyography (EMG) system. The muscles analysed will be Gluteus Maximus, Multifidus, Biceps Femoris, Semimembranosus, Rectus Femoris, Vastus Lateralis, Gastrocnemius and Tibialis Anterior. Each participant will be required to complete 4 x 40–50m sprint running trials the data from which will be used to normalise the EMG data (Albertus-Kajee *et al.*, 2011). The forces exerted on the dominant lower limb during each sprinting trial will also be measured using a force plate embedded in the running track in NIAC. A six-minute rest period will be given between each sprinting trial (Mendiguchia *et al.*, 2014). All trials will be captured using a video camera to determine stride length, stride frequency and distinguish between the stance and swing phases of the gait cycle. The video will be stored securely and the footage will be restricted strictly to those required for the data analysis. The data collection will take approximately 75 minutes per participant.

Visit 2 - the second aim of this study is to evaluate the physiological characteristics of hamstring training exercises. The exercises included in the study will be chosen based on their theoretical link to hamstring function and use in the prevention and treatment of hamstring strain injuries. The EMG set up as described for visit one will be used to evaluate hamstring muscle function during a series of hamstring training exercises. The exercises will be grouped into traditional exercises including the Nordic Curl, Deadlift and Hamstring curl; and novel hamstring exercises including the Gluteal-Hamstring raise, Single-Leg Bridge and Upright Single-Leg Good Morning. All participants will complete one set of each exercise, performing three successive repetitions and using a load based on an estimated six repetition maximum (RM). Five minutes rest will be given between each different exercise (Ebben, 2009). Randomizing the order of the exercises, using three repetitions and providing a five-minute rest between all exercises will reduce order and any effects of fatigue (Ebben, 2009). Furthermore, by adopting this method the EMG data for the exercises will be less affected by fatigue produced by the previous exercise(s) (Glenn *et al.,* 1999). All exercises will be recorded using a video camera to synchronize the muscle activity with the different phases of the exercises. The video will be stored securely and the footage will be restricted strictly to those required for the data analysis. The data collection will take approximately 75 minutes per participant.

The final aim of this study is to compare the findings of the data collected during the sprint trials and hamstring exercises so that training exercises that most closely replicate the hamstring function in sprinting can be identified. The participants will not be directly involved at this stage however they will need to be informed of this part of the study and give consent for their data to be used.

A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
Click here to enter text.	

B PREVIOUS EXPERIENCE
B1 What previous experience of research involving human participants relevant to this project do you have?
I have previously completed two BSc dissertations and one MSc dissertation all of which involved the use of human participants. One of the BSc projects included the use of an Isokinetic Dynamometer and the MSc project required the use of an Isokinetic Dynamometer, EMG and a Vicon system – all of which will be used in the current proposed study.
B2 **Student project only** What previous experience of research involving human participants relevant to this project does your supervisor have?
Dr Craig Ranson (DoS) has extensive research experience in biomechanical and musculoskeletal assessment within injury prevention. Dr Isabel Moore has researched and published in the area of lower limb running mechanics using athletic populations. Additionally, she completed her PhD in the field of neuromuscular characteristics of runners. Dr Jon Oliver has extensive experience of conducting research and has previously supervised students undertaking similar research. This has included research examining aspects of sprinting, fatigue and injury. Some of this work has been funded by UEFA and FIFA and includes research with elite and high-level athletes. Dr Ian Bezodis has extensive research experience in the field of Biomechanics. His specific research interests include: 1) Evaluating and characterising elite sprinting 2) Investigating the step length-step frequency relationship in elite sprinting and 3) Understanding critical performance factors through the use of inverse dynamic models of sprint technique.

C POTENTIAL RISKS
C1 What potential risks do you foresee?
The participants may experience fatigue as a result of completing the sprinting trials and also muscle soreness as a result of completing the hamstring exercises during data collection. There is also a potential risk of muscle strain injury, however the exercises being analysed are believed to help injury prevention. The data collection process presents no more risk than the participants experience during a routine training session. The EMG electrodes will be attached directly to the skin with tape and therefore there is a chance that some of the participants may have a tape allergy.
C2 How will you deal with the potential risks?
Each participant will complete a standardised 15minute warm-up prior to taking part in the study. A period of recovery will be provided after each running trial and each different

exercise. Furthermore, only three repetitions of each exercise will be completed thus avoiding fatigue. There will be two physiotherapists present during all data collection procedures and the NIAC staff have up to date first aid qualifications. Each participant will be advised to stretch after taking part in the data collection process. The EMG electrodes will be attached to the skin using a hypoallergenic tape to avoid any adverse skin reactions.

When submitting your application, you **MUST** attach a copy of the following:

- All information sheets
- Consent/assent form(s)

Refer to the document ***Guidelines for obtaining ethics approval*** for further details on what format these documents should take.

APPENDIX 2 PARTICIPANT INFORMATION SHEET (STUDIES 1-3)

Title of research project:

Hamstring Function in Elite Sprint Running: A longitudinal intervention for training and injury prevention

CMU approval number: 15/1/03R

What is the purpose of the study?

Hamstring strain injuries (HSI) are the most common muscle injury in sport with high-speed running being the most common activity at time of injury. HSI accounts for between six and 29% of all injuries reported in Australian Rules Football, Rugby Union, Soccer, Cricket and track sprinting. Hamstring function is crucial to sprint performance meaning hamstring injury has significant consequences on an athlete's performance However, the precise mechanism and timing of hamstring strain in sprinting is unknown.

The re-injury rate for HSI has been reported as being as high as 31%. The risk of re-injury is reported to be most significant within the first two weeks of return to sport and reoccurrences are often more severe than the initial injury. This has great consequences in terms of finance and the time that the athlete loses from both training and competition. With HSI injury and re-injury being such a common occurrence in sport it suggests that current prevention and rehabilitation programmes which target this injury have not been successful, therefore the challenge of optimising the management HSI remains.

Aim of the study

The aim of this study to analyse the level and timing of hamstring muscle activation during sprinting and a range of hamstring exercises to determine which are the most appropriate for hamstring injury prevention training and rehabilitation.

Your participation in the research project

Why you have been asked?

As HSI is a common sporting injury this study is recruiting rugby players in an attempt to positively influence the management of these injuries, from a prevention and rehabilitation point of view.

Individuals will be eligible to participate in the study if they:

1) Are currently playing rugby at a minimum of university level
2) Take part in regular training (minimum of 45minutes x 3 times per week)
3) Have no history of lower limb injury that has caused more than five days absence from training or matches in the last 12 months
4) Have no history of lower limb surgery
5) Are aged between 18-30 years old
6) Are fit and healthy at the time of the testing

What happens if you want to change your mind?

If you decide to join the study you can change your mind and stop your participation at any time - we will completely respect your decision. If you want to withdraw from the study we ask that you contact us via the details at the end of this of this form to let us know. There are absolutely no penalties for withdrawing from the study.

What would happen if you join the study?

You will need to attend the National Indoor Athletics Centre (NIAC) at the Cardiff School of Sport, in Cardiff Metropolitan University for the purpose of data collection. Due to the nature of the project data will be collected on two separate occasions. Prior to any data collection you will be asked to read the information sheet and will be given the opportunity to ask any questions prior to signing a consent form. The experimental protocol will then be explained to you to ensure that you understand the procedure. You will need to wear a pair of shorts (preferably cycling shorts), a t-shirt and trainers for the purpose of data collection. On providing written consent for participation and prior to any data collection your weight and height will be measured. You will then be given a demonstration of the different tasks involved and will have time to familiarize yourself with the tasks. The tasks involved will be different at each visit to NIAC.

The activity of four thigh muscles, one buttock muscle, one back muscle, one shin and one calf muscle will be analysed during the performance of all tasks (described below). This will be achieved by electromyography (EMG) which involves attaching electrodes to your skin. The skin surrounding the site of electrode placement will be cleaned and shaved if appropriate prior to electrode application to help ensure a good skin contact. The procedure of EMG analysis will follow published instrumentation guidelines.

Data Collection Procedure

During your visit to NIAC you will be asked to complete four x 40m sprint running trials. Prior to the sprint running trials you will complete a standardised 15-minute warm-up. Between each sprint trial you will be given a four-minute rest period. All trials will be recorded using a video camera. After the sprint trials you will asked to complete three repetitions of six different hamstring training exercises with the EMG electrodes in place as during your sprint trials. Five minutes rest will be given between each different exercise and all exercises will be recorded using a video camera. The data collection will take approximately two hours. The results obtained from the sprinting trials will be compared to the findings collected during the hamstring training exercises. You will not be directly involved at this stage however aware of this element of the study and to provide consent for your data to be used.

Are there any risks?

There are very few risks associated with this study. You may however experience fatigue as a result of completing the sprinting trials and also muscle soreness as a result of completing the hamstring exercises during data collection. There is also a potential risk of muscle strain injury. However, the data collection process presents no more risk than you experience during a routine training session. You will be asked to complete a standardised 15-minute warm-up prior to taking part in the study and a period of recovery will be provided after each running trial and each different exercise to minimise fatigue as much as possible. You will be advised to stretch after taking part in the data collection process. The EMG electrodes will be attached to the skin using a hypoallergenic tape to avoid any adverse skin reactions. There will be medically trained staff present during all data collection procedures should you need assistance.

Your rights

Joining the study does not mean you have to give up any legal rights.

Any special precautions needed?

You will be asked not to train or consume alcohol in the 48 hours prior to data collection.

What happens to the results?

The findings of the study will be presented in the form of a PhD research project. The study may be submitted for publication in appropriate scientific journals and also as a poster for presentation at conferences.

Are there any benefits from taking part?

There will be no individual benefit from taking part in this study. It is hoped however that the results of the study will inform the management of HSI and improve both prevention and rehabilitation programmes by using the most appropriate hamstring training exercises.

How we protect your privacy:

All the information we obtain from you is strictly confidential, and everyone working on the study will respect your privacy. The information and data we have about each participant will be coded so that you cannot be identified individually. Copies of all data collected during the testing period will be stored centrally within a secure holding location in Cardiff Metropolitan University. Only the principal researcher and her supervisory team will be able to access the data once stored in Cardiff Metropolitan University. Once the study has been completed and the information has been analysed, all the information (both hard copy and electronic) will be destroyed. We will keep a copy of your signed consent form for 10 years, because we are required to do so by the University.

PLEASE NOTE: *YOU WILL BE GIVEN A COPY OF THIS SHEET TO KEEP, TOGETHER WITH A COPY OF YOUR CONSENT FORM*

Contact Details: **Researcher Name** Adeline Phillips (aphillips@cardiffmet.ac.uk)
Supervisor Name Dr Craig Ranson (cranson@cardiffmet.ac.uk)

APPENDIX 3 – PARTICIPANT CONSENT FORM (STUDIES 1-3)

PARTICIPANT CONSENT FORM

Reference number: 15/1/03R

Participant name or study ID number:

Title of project: Hamstring function in elite sprint running: A novel longitudinal intervention for training and injury prevention

Name of researcher: Adeline Phillips

Participant to complete this section: Please initial each box.

1. I confirm that I have read and understood the information sheet for the above study. I have had the opportunity to consider the information and to ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw from the study at any time, without giving any reason. ☐

3. I agree to be filmed during the period of data collection. ☐

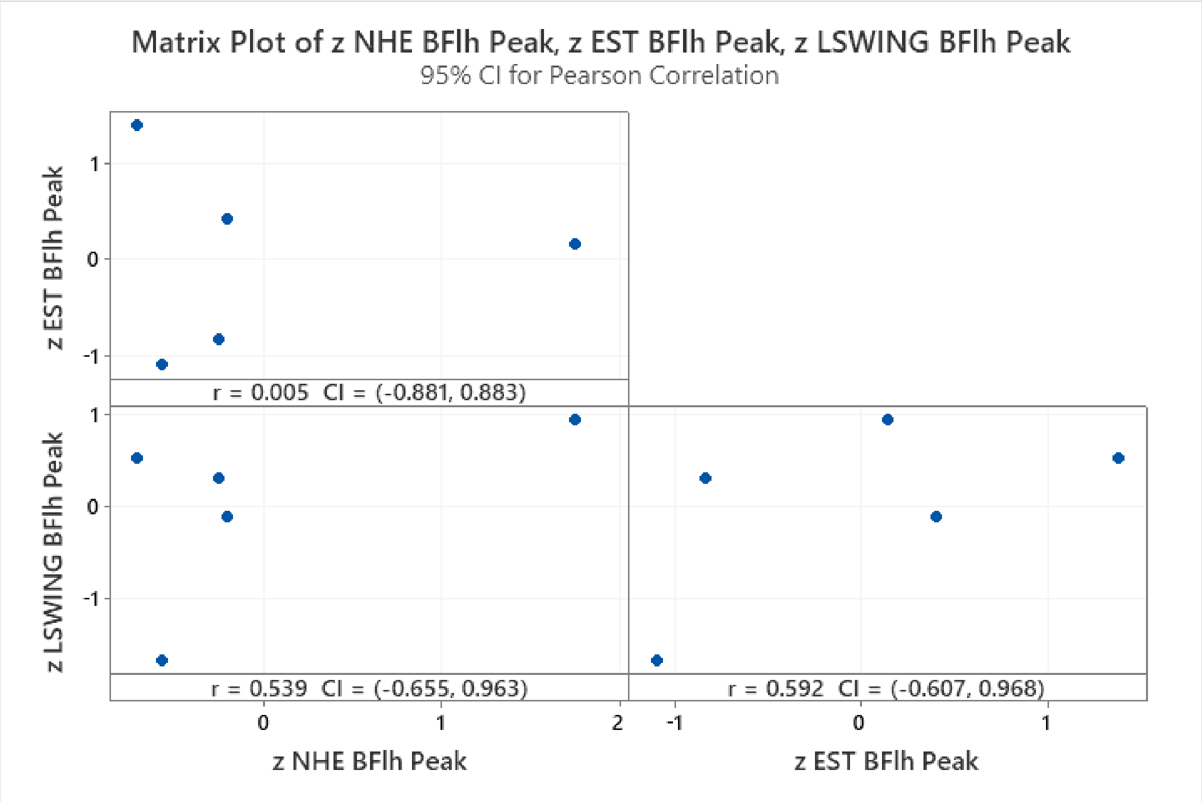
4. I agree to take part in the above study. ☐

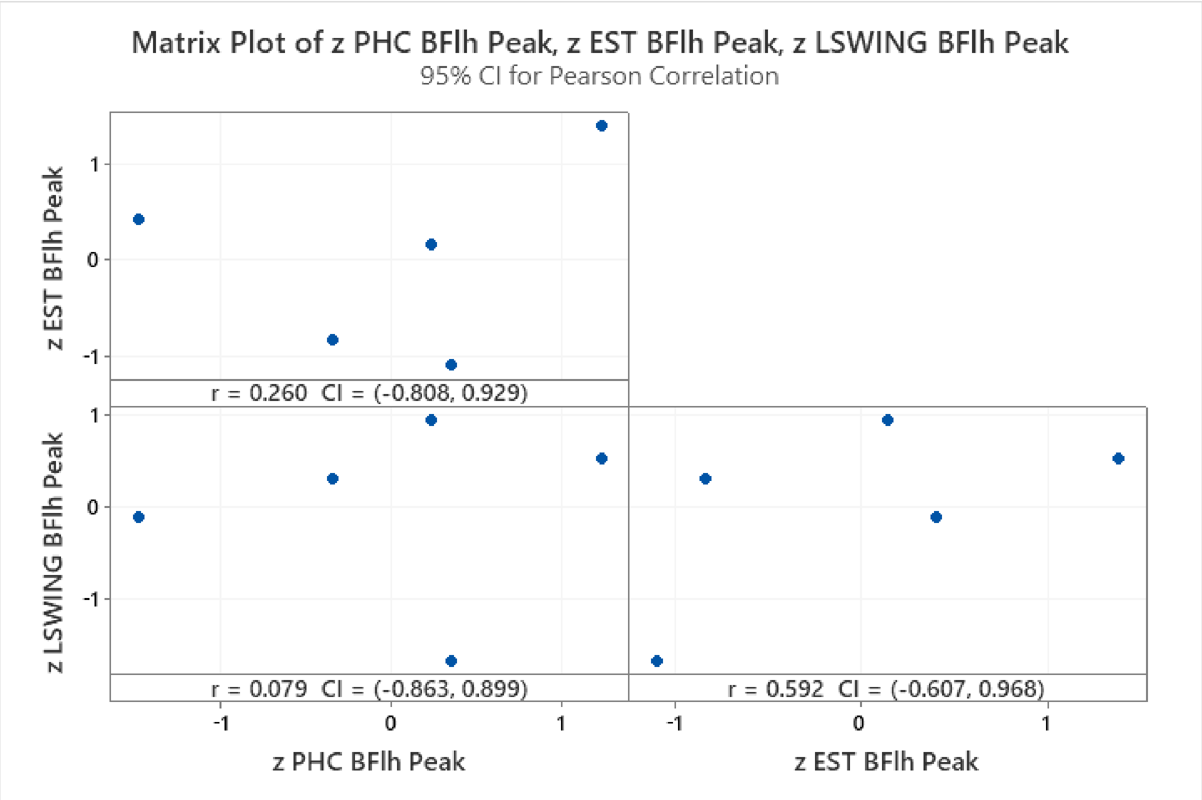
Signature of participant	**Date**
Name of person taking consent	**Date**
Signature of person taking consent	**Date**

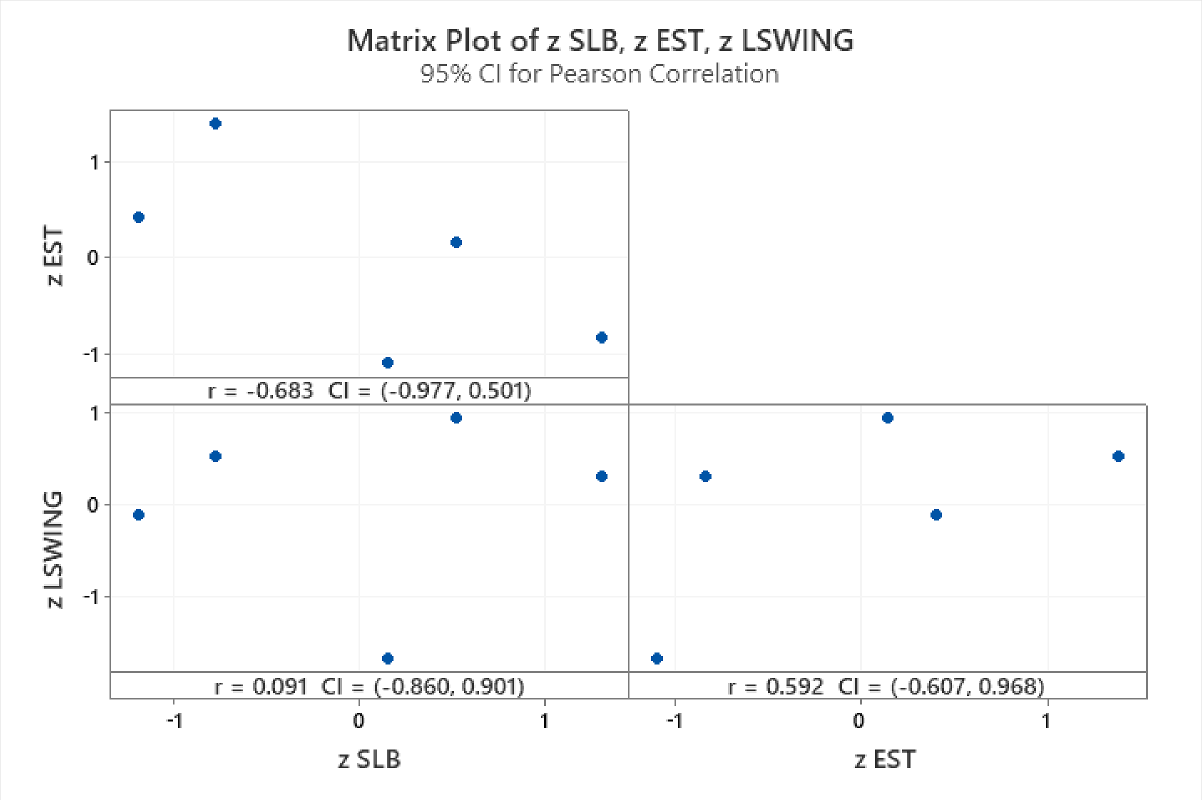
When completed, 1 copy for the participant and 1 for the researcher

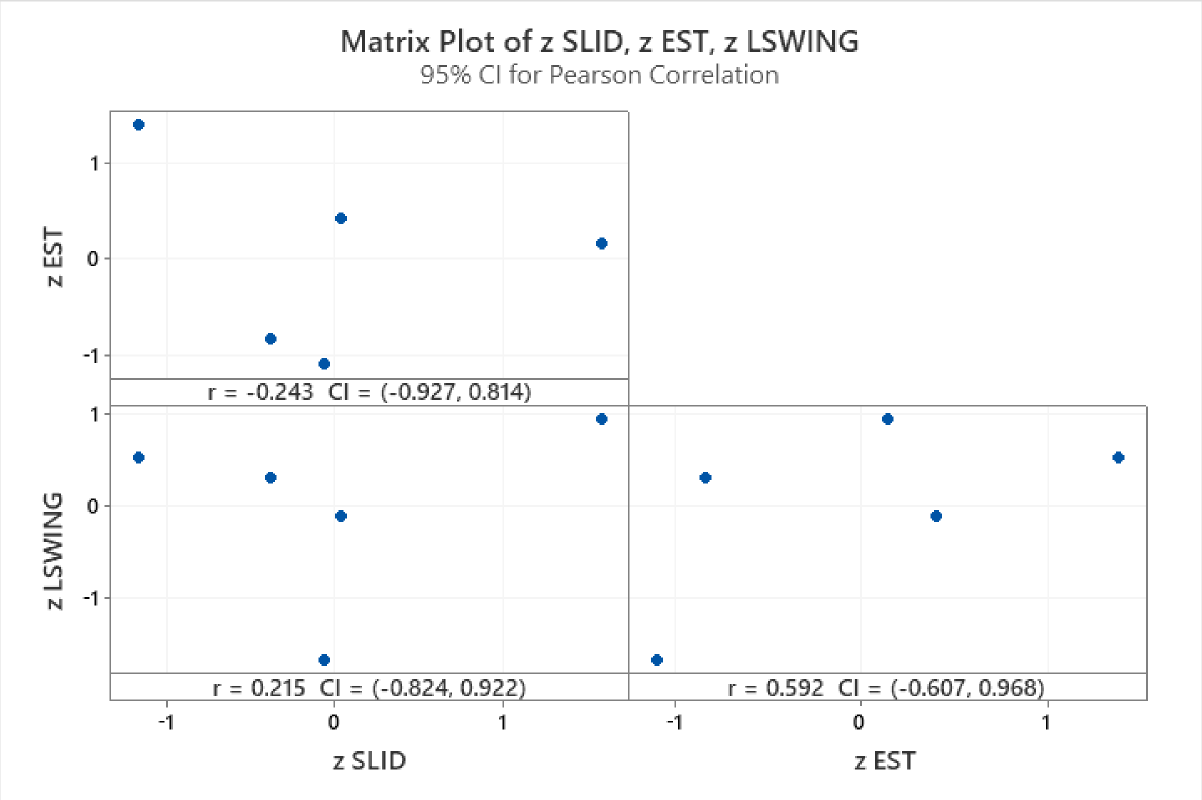
APPENDIX 4 – SCATTER PLOTS – NORMALISED PEAK EMG (STUDY 3)

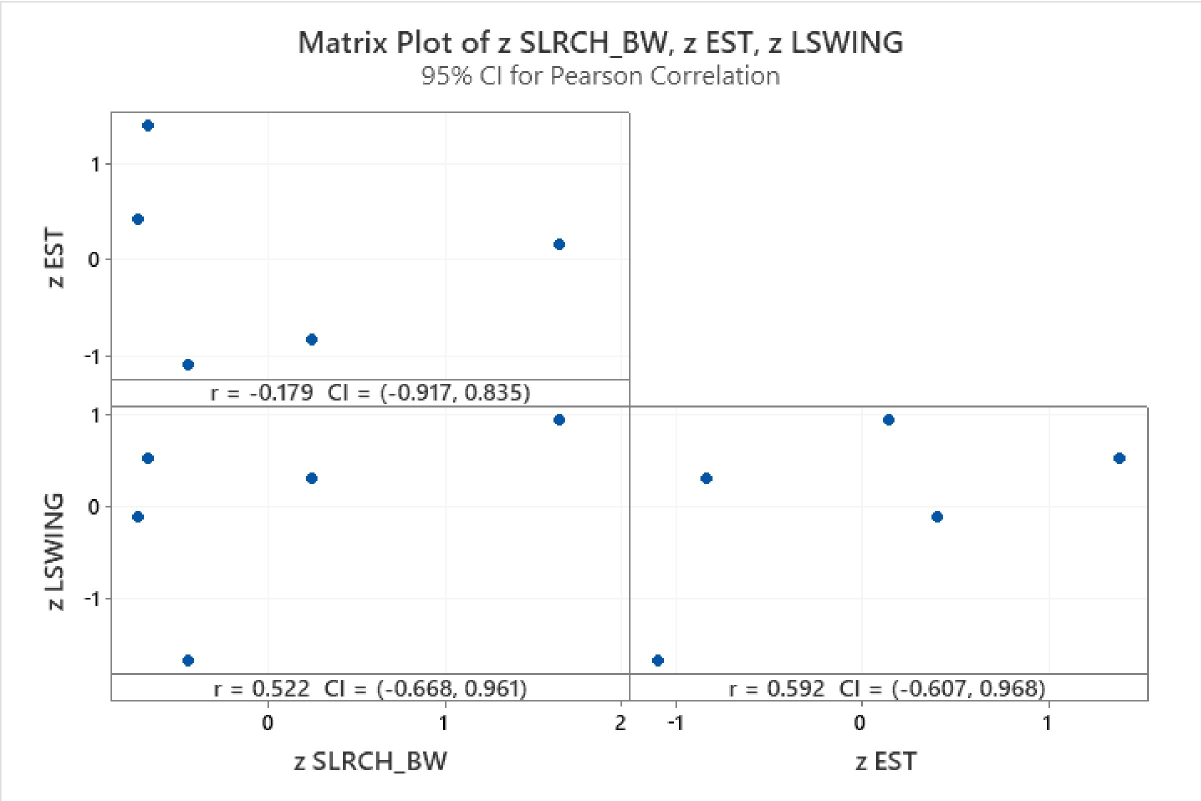
BFlh scatter plots – Peak nEMG – Sprint phase and individual exercises

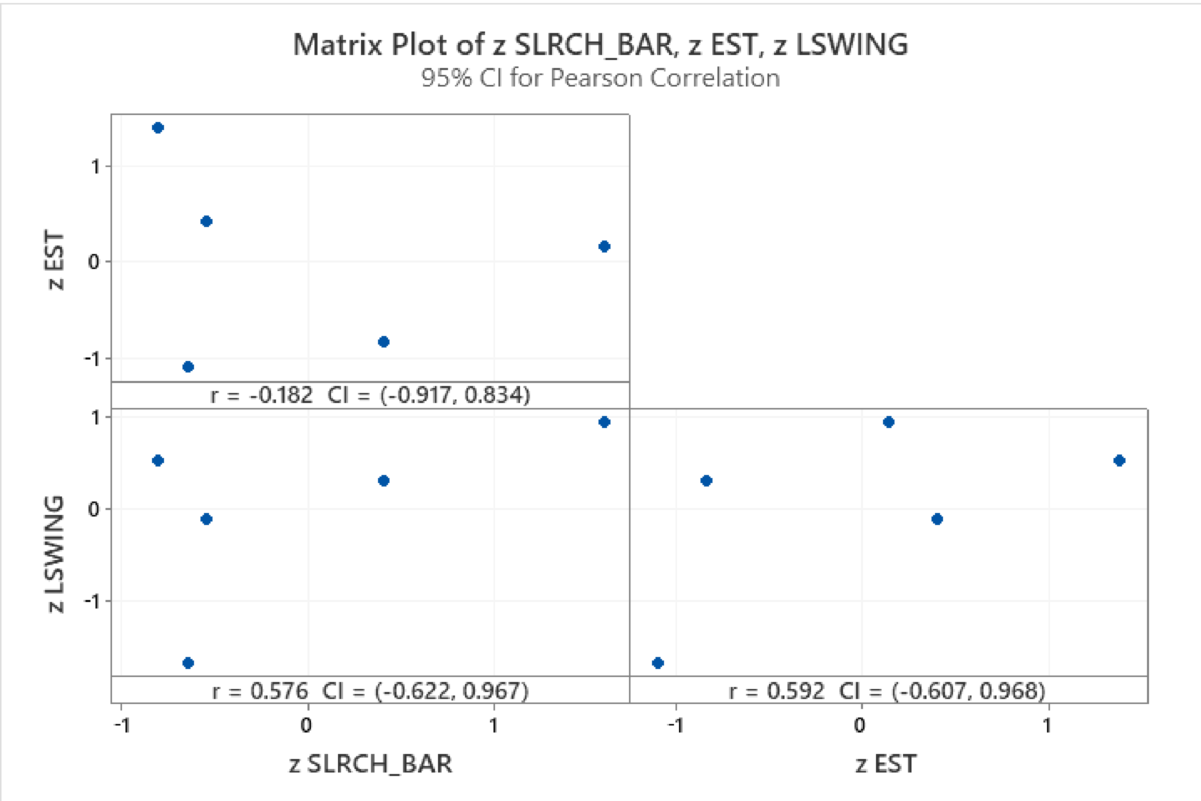




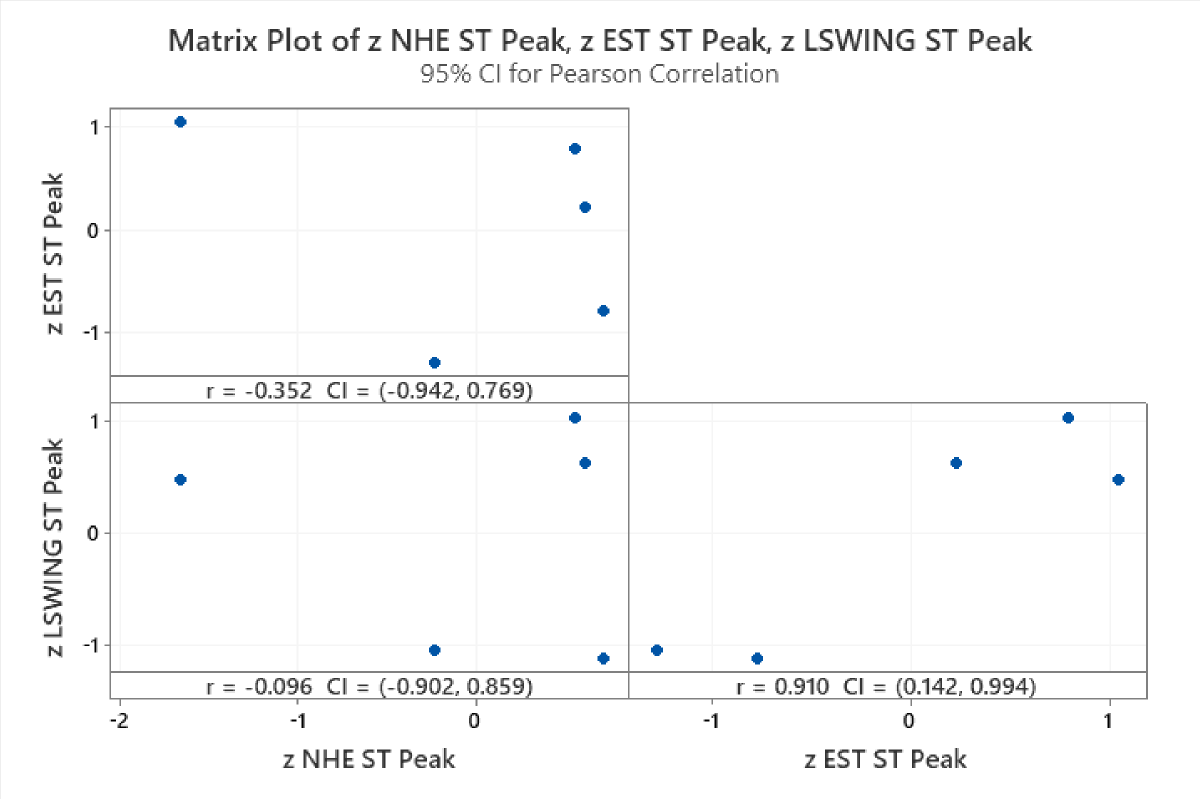

Matrix Plot of z SLB, z EST, z LSWING
95% CI for Pearson Correlation
z EST
z LSWING
r = -0.683 CI = (-0.977, 0.501)
r = 0.091 CI = (-0.860, 0.901)
r = 0.592 CI = (-0.607, 0.968)
z SLB
z EST

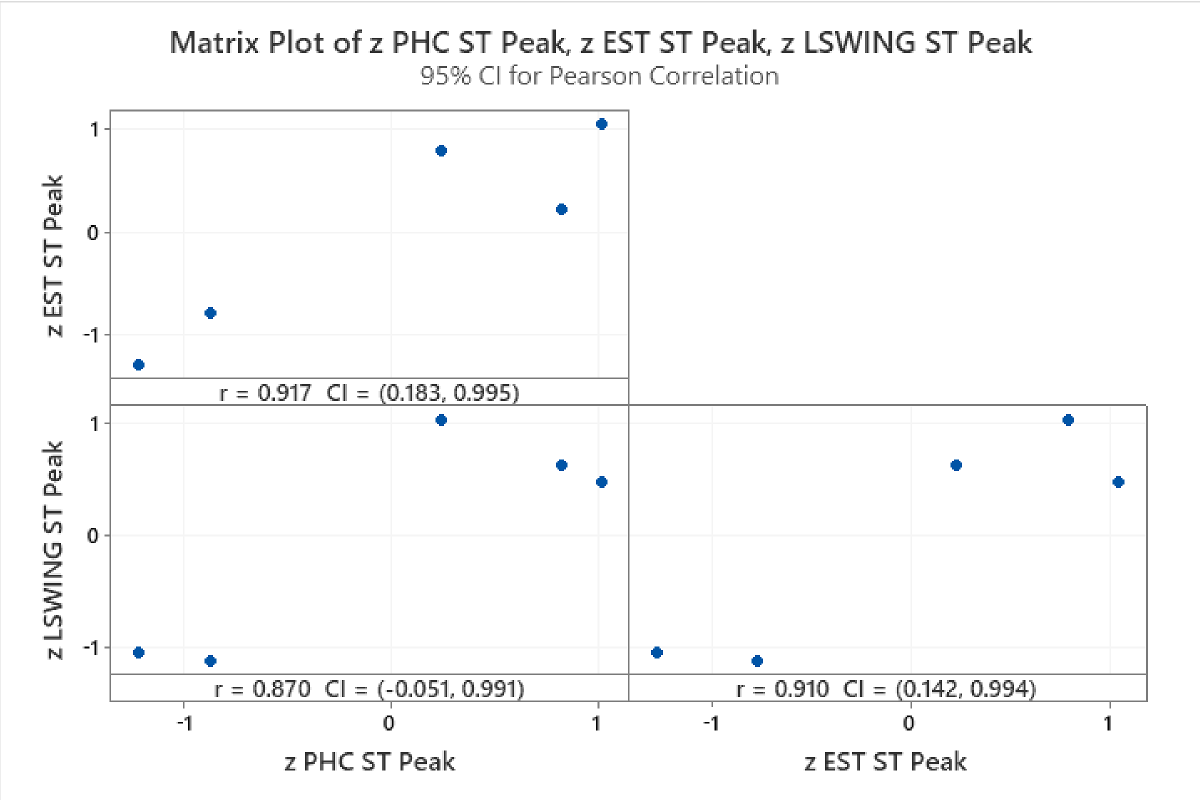

Matrix Plot of z SLID, z EST, z LSWING
95% CI for Pearson Correlation
z EST
z LSWING
r = -0.243 CI = (-0.927, 0.814)
r = 0.215 CI = (-0.824, 0.922)
r = 0.592 CI = (-0.607, 0.968)
z SLID
z EST

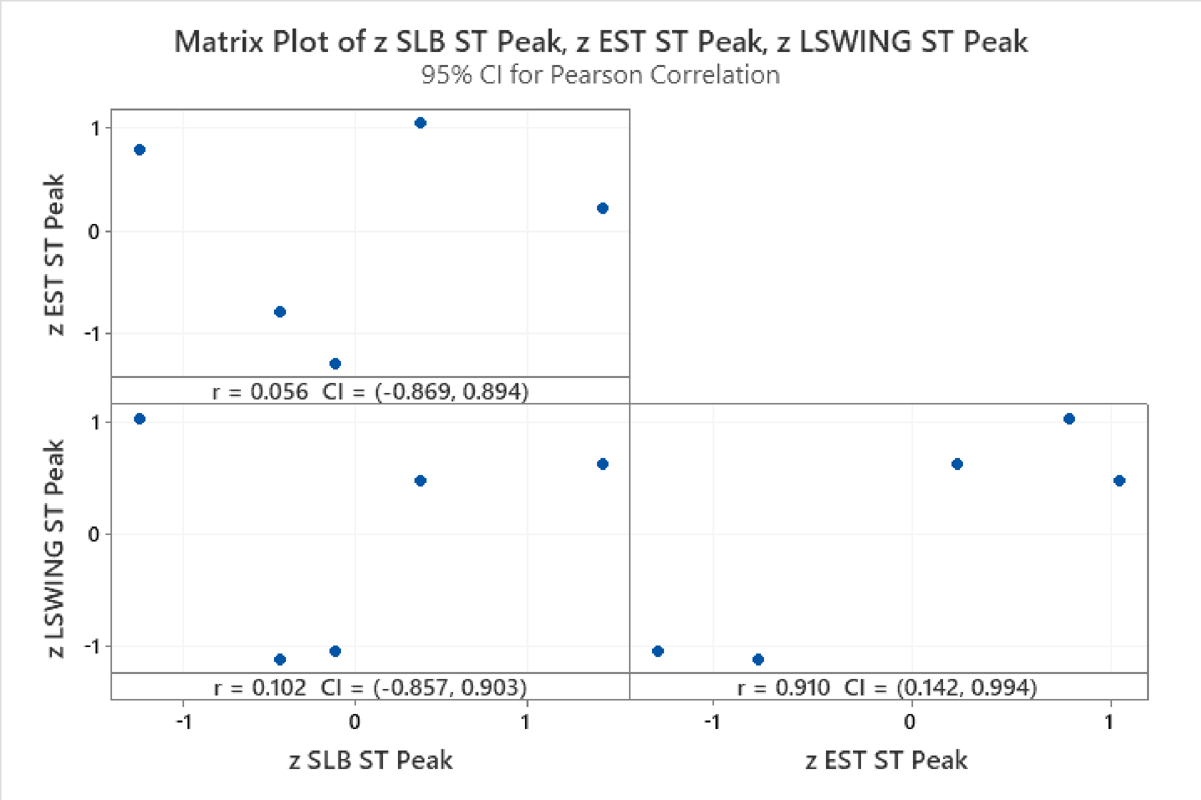

Matrix Plot of z SLRCH_BW, z EST, z LSWING
95% CI for Pearson Correlation
z EST
z LSWING
r = -0.179 CI = (-0.917, 0.835)
r = 0.522 CI = (-0.668, 0.961)
r = 0.592 CI = (-0.607, 0.968)
z SLRCH_BW
z EST

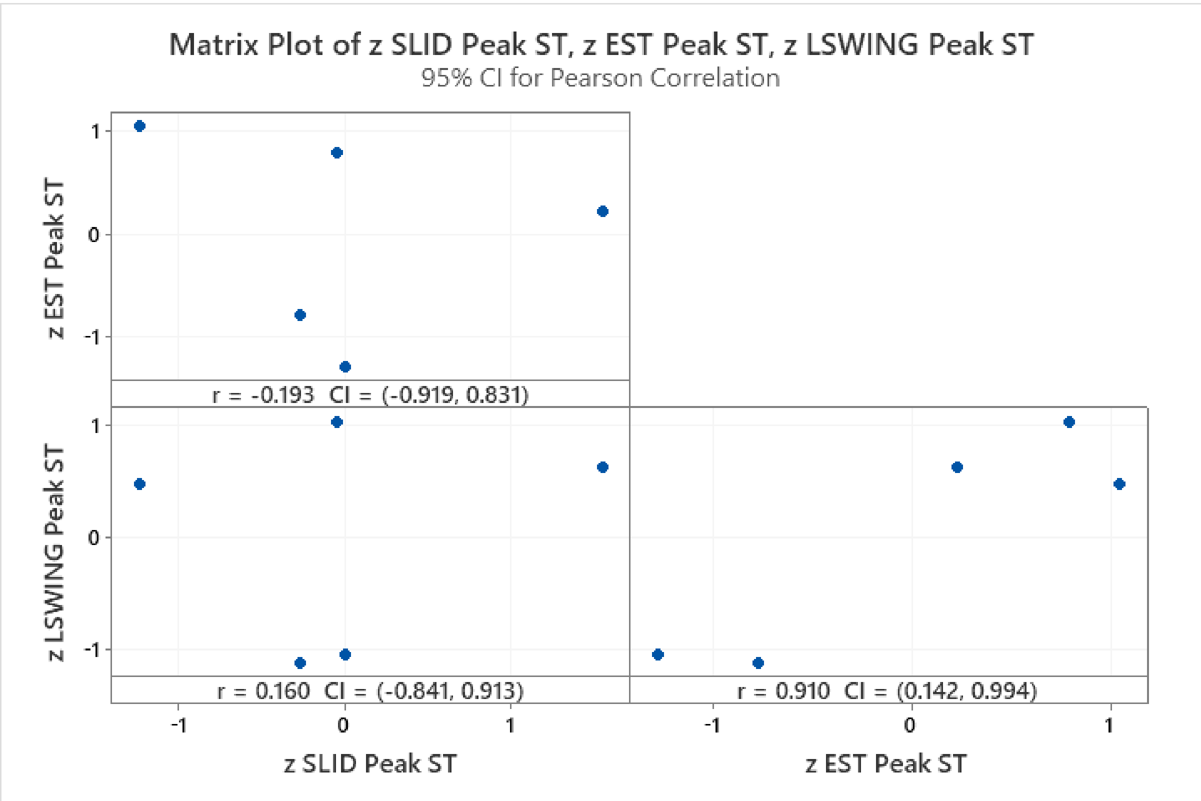

Matrix Plot of z SLRCH_BAR, z EST, z LSWING
95% CI for Pearson Correlation
z EST
z LSWING
r = -0.182 CI = (-0.917, 0.834)
r = 0.576 CI = (-0.622, 0.967)
r = 0.592 CI = (-0.607, 0.968)
z SLRCH_BAR
z EST

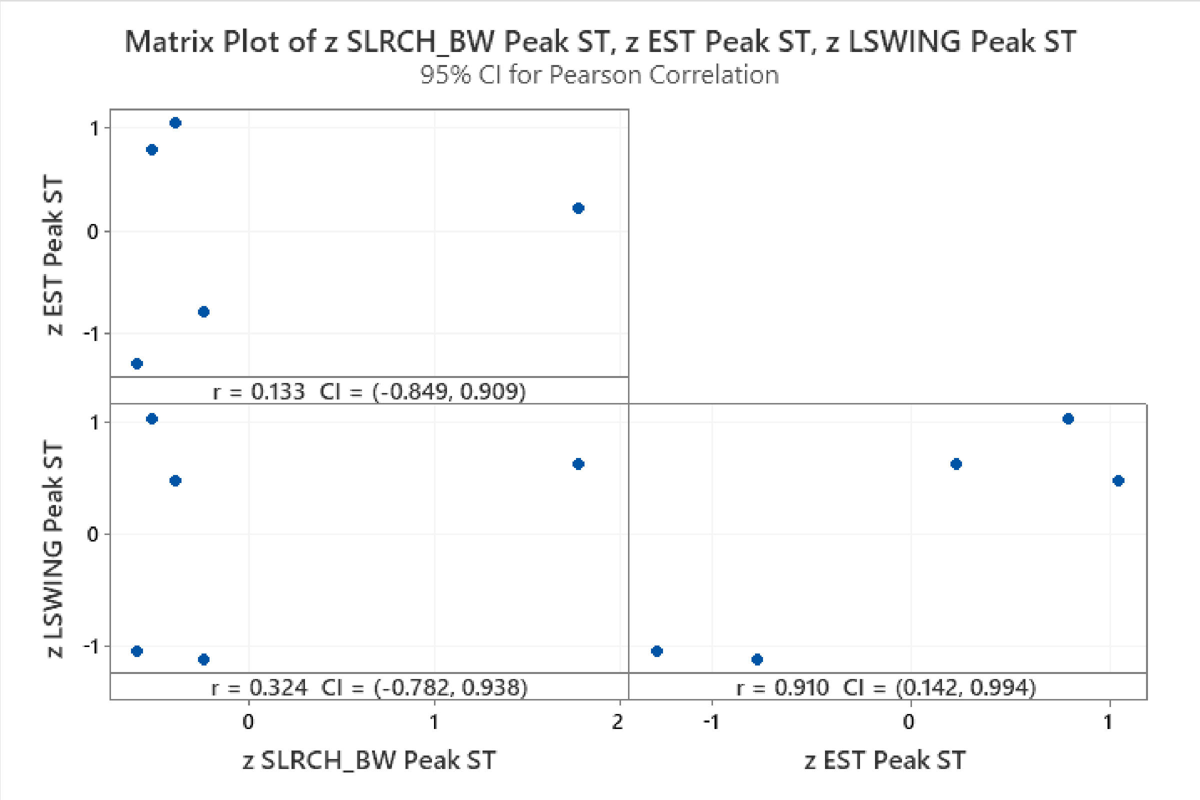
ST scatter plots – Peak nEMG – Sprint phase and individual exercises

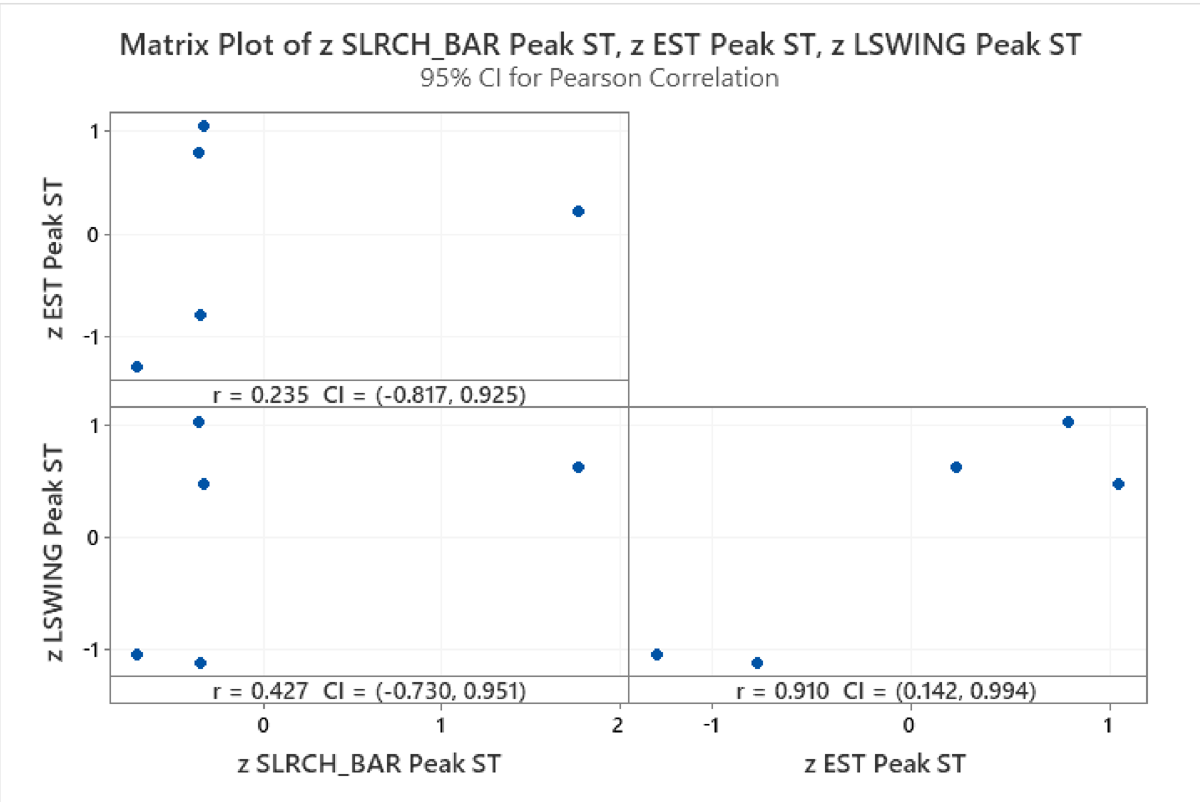




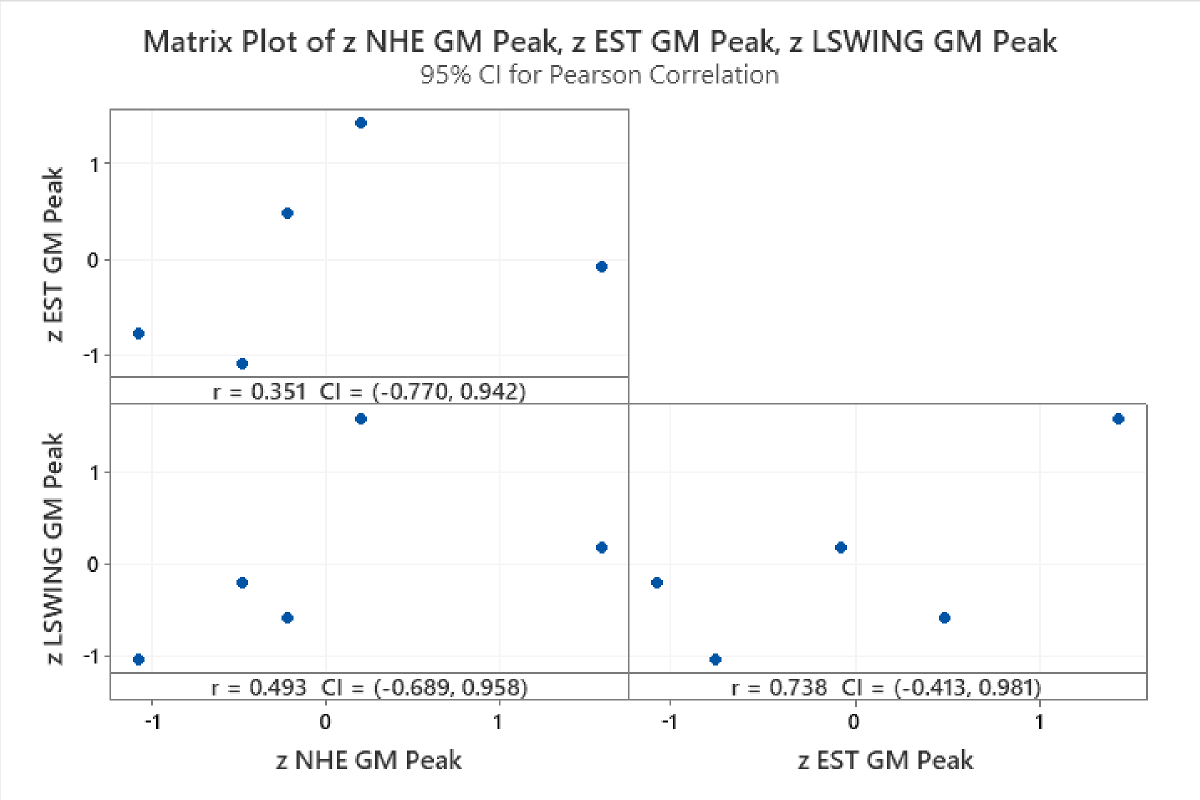

Matrix Plot of z SLB ST Peak, z EST ST Peak, z LSWING ST Peak
95% CI for Pearson Correlation
z EST ST Peak
z LSWING ST Peak
r = 0.056 CI = (-0.869, 0.894)
r = 0.102 CI = (-0.857, 0.903)
r = 0.910 CI = (0.142, 0.994)
z SLB ST Peak
z EST ST Peak

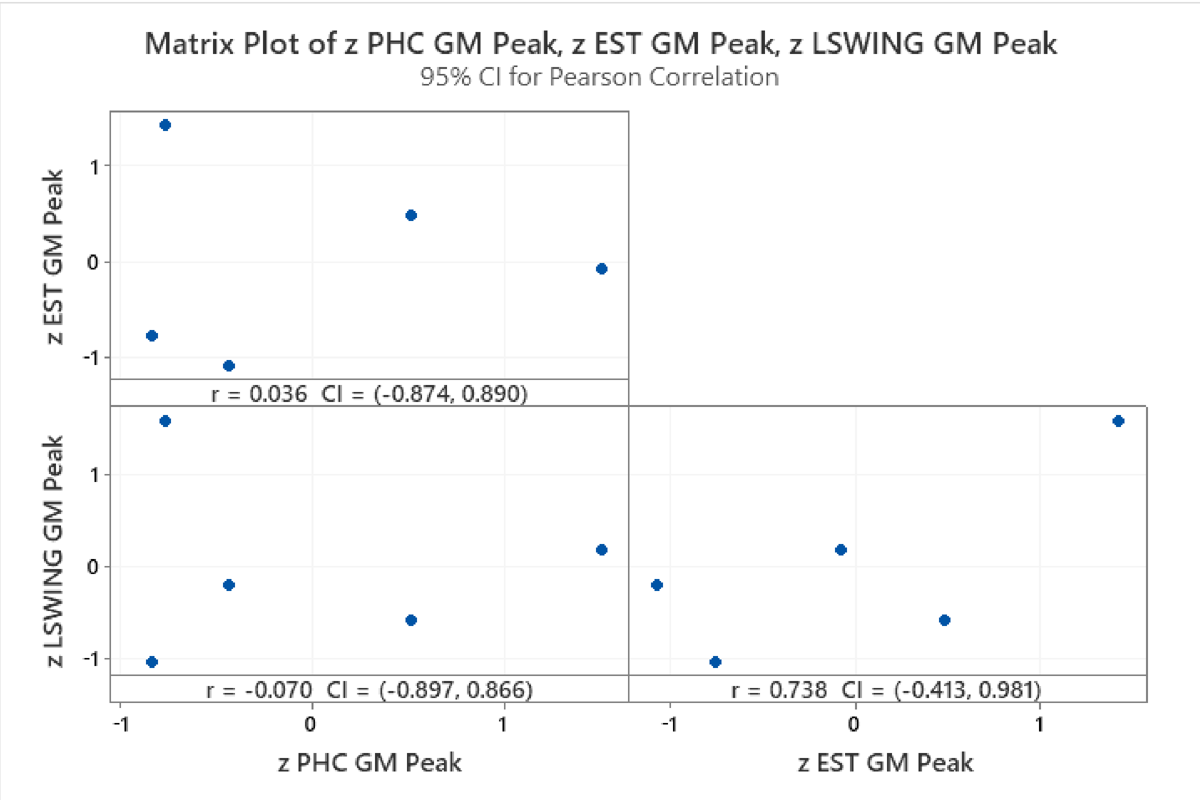

Matrix Plot of z SLID Peak ST, z EST Peak ST, z LSWING Peak ST
95% CI for Pearson Correlation
z EST Peak ST
z LSWING Peak ST
r = -0.193 CI = (-0.919, 0.831)
r = 0.160 CI = (-0.841, 0.913)
r = 0.910 CI = (0.142, 0.994)
z SLID Peak ST
z EST Peak ST

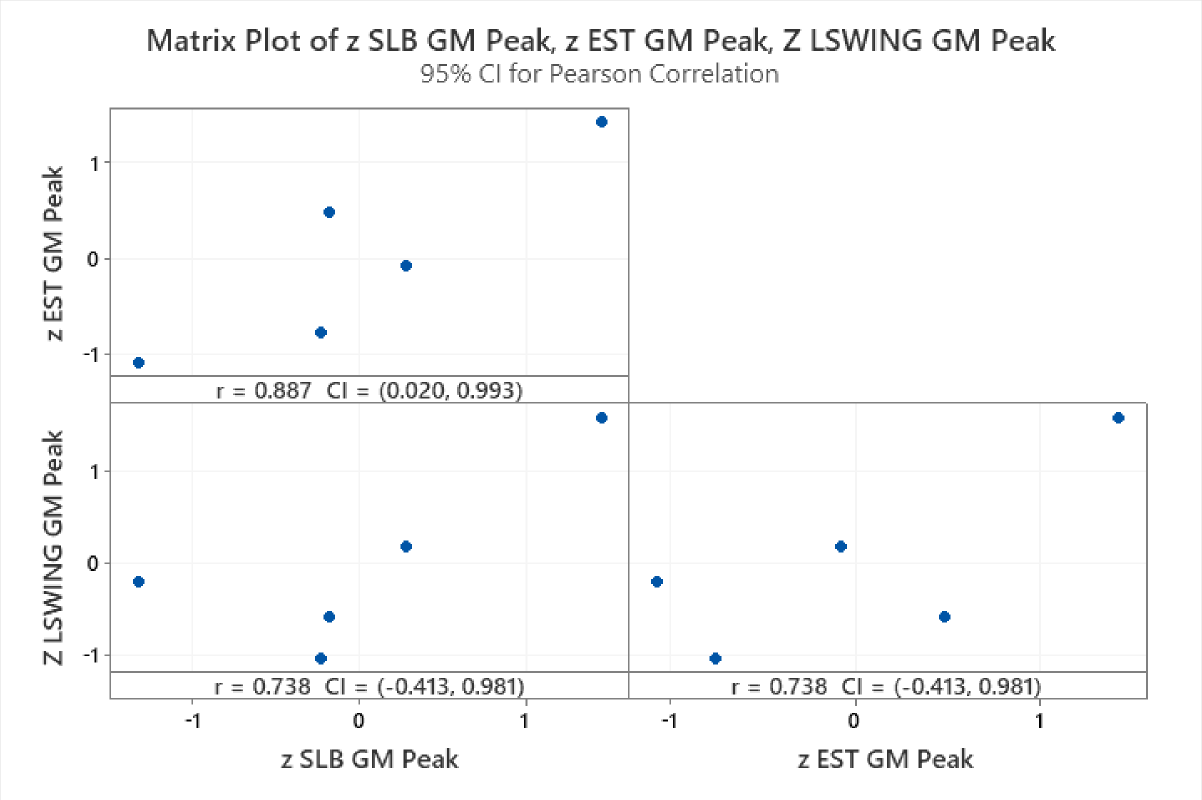

Matrix Plot of z SLRCH_BW Peak ST, z EST Peak ST, z LSWING Peak ST
95% CI for Pearson Correlation
z EST Peak ST
z LSWING Peak ST
r = 0.133 CI = (-0.849, 0.909)
r = 0.324 CI = (-0.782, 0.938)
r = 0.910 CI = (0.142, 0.994)
z SLRCH_BW Peak ST
z EST Peak ST

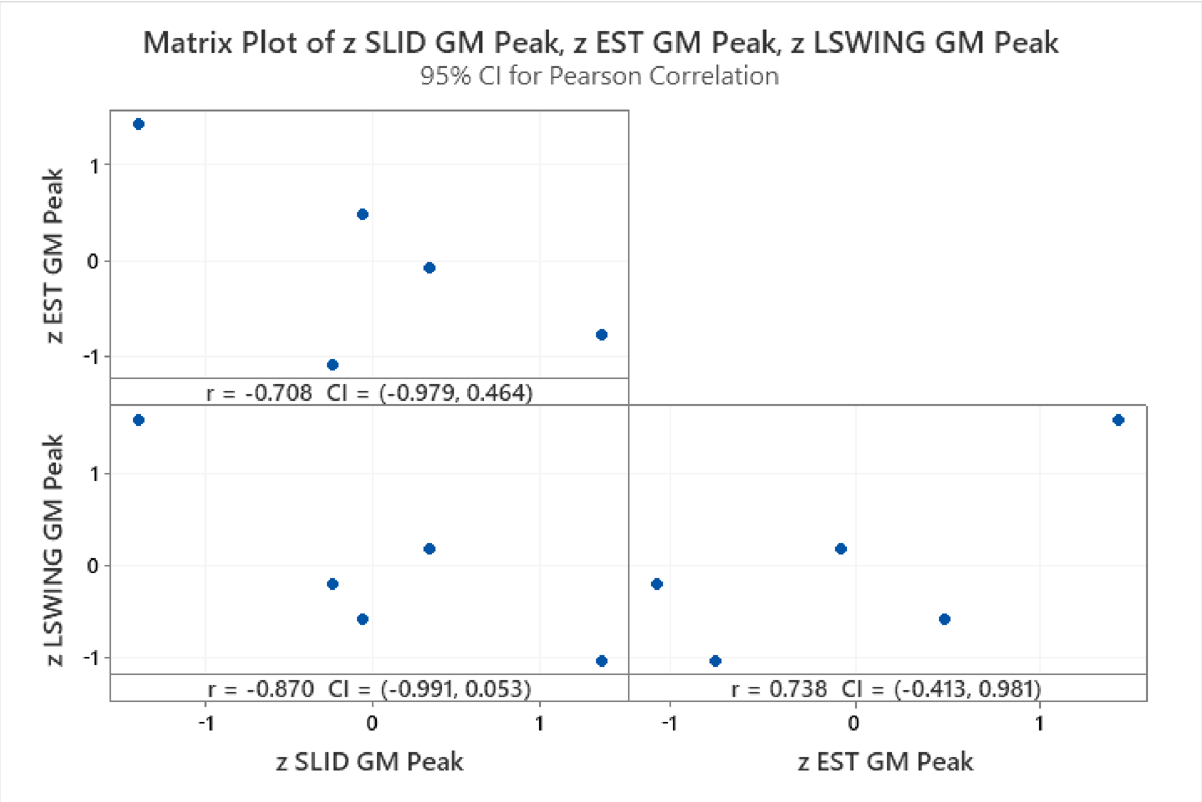

Matrix Plot of z SLRCH_BAR Peak ST, z EST Peak ST, z LSWING Peak ST
95% CI for Pearson Correlation
z EST Peak ST
z LSWING Peak ST
r = 0.235 CI = (-0.817, 0.925)
r = 0.427 CI = (-0.730, 0.951)
r = 0.910 CI = (0.142, 0.994)
z SLRCH_BAR Peak ST
z EST Peak ST

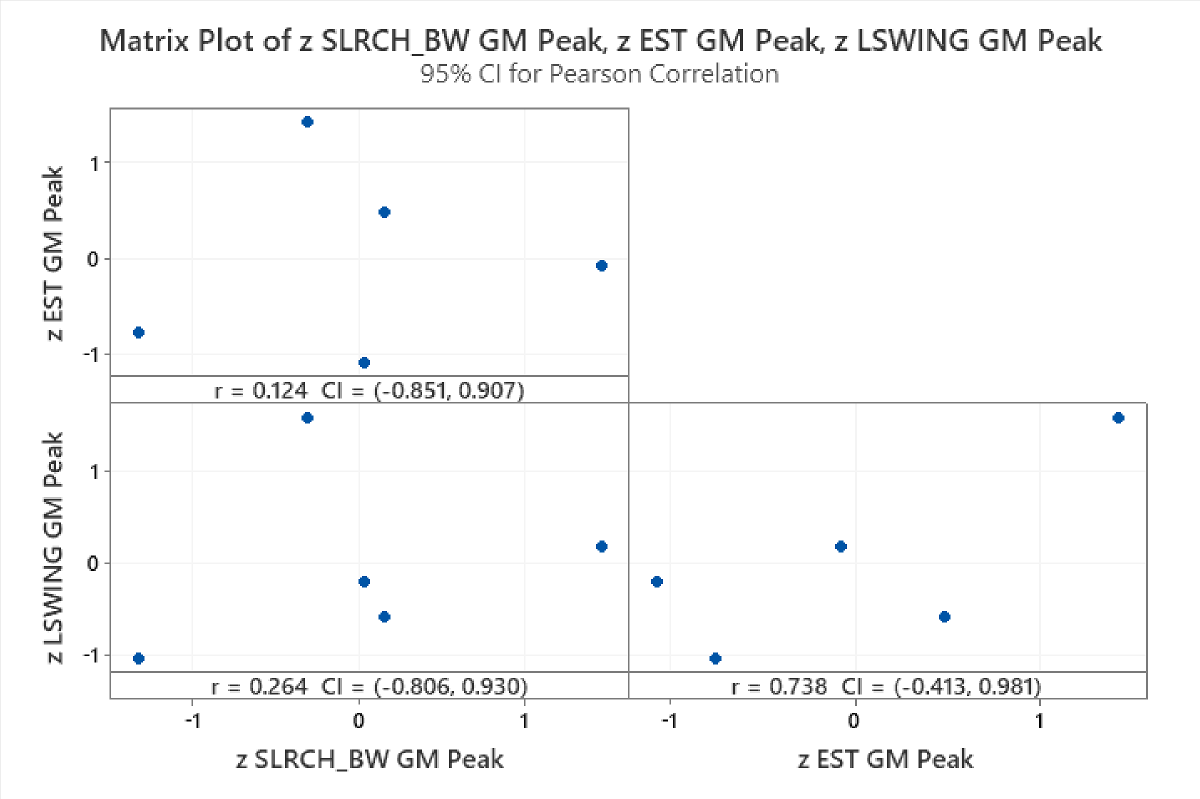
GM scatter plots – Peak nEMG – Sprint phase and individual exercises

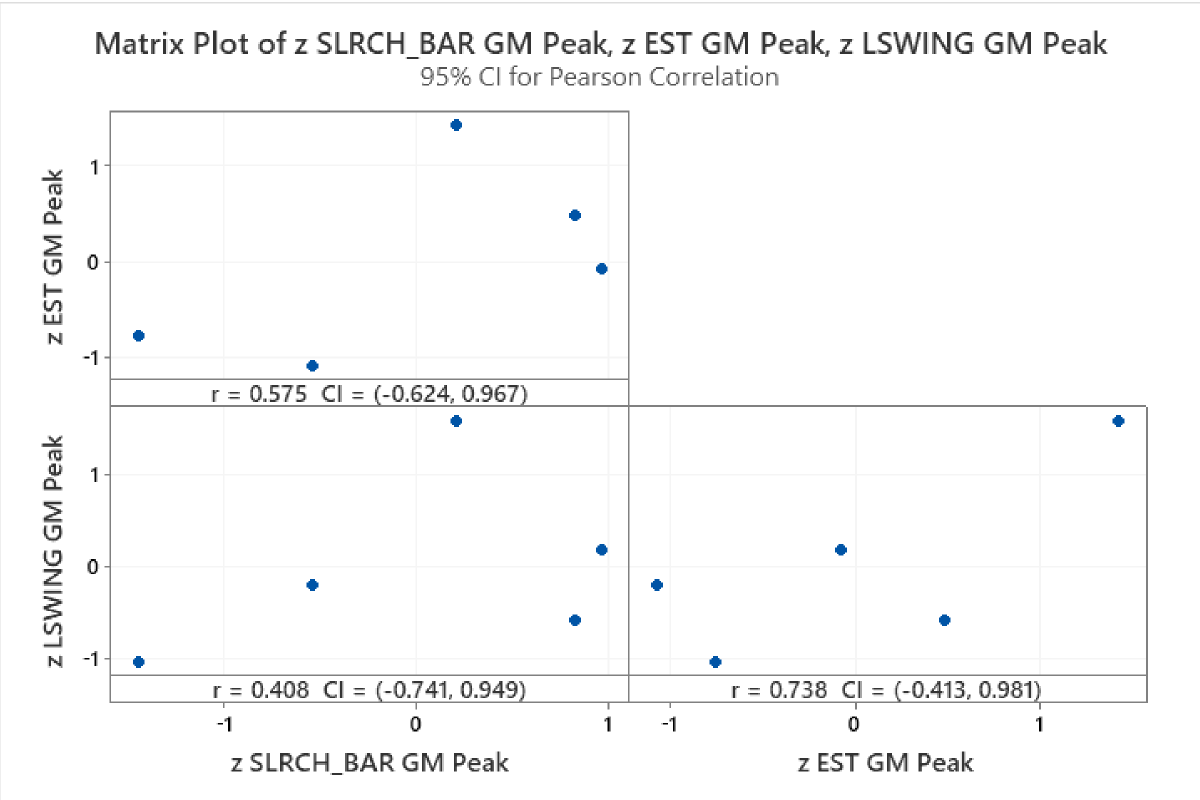




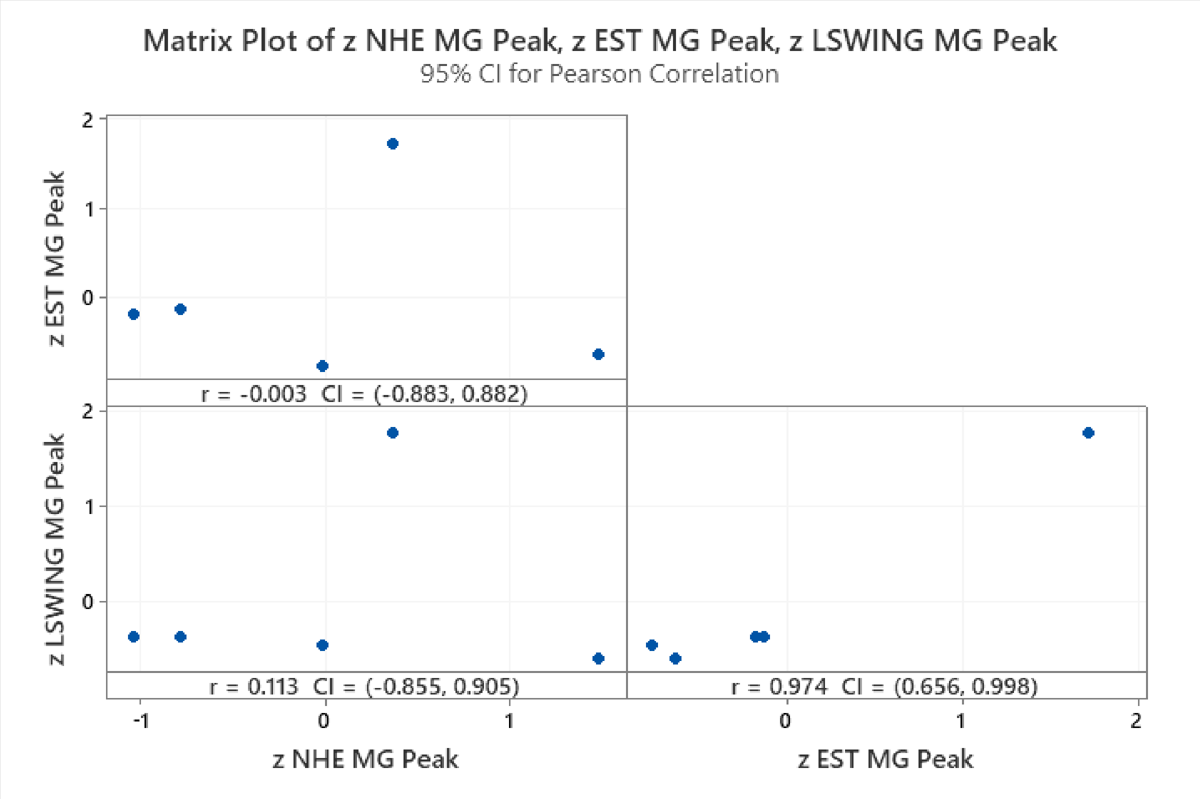

Matrix Plot of z SLB GM Peak, z EST GM Peak, Z LSWING GM Peak
95% CI for Pearson Correlation
z EST GM Peak
Z LSWING GM Peak
r = 0.887 CI = (0.020, 0.993)
r = 0.738 CI = (-0.413, 0.981)
r = 0.738 CI = (-0.413, 0.981)
z SLB GM Peak
z EST GM Peak

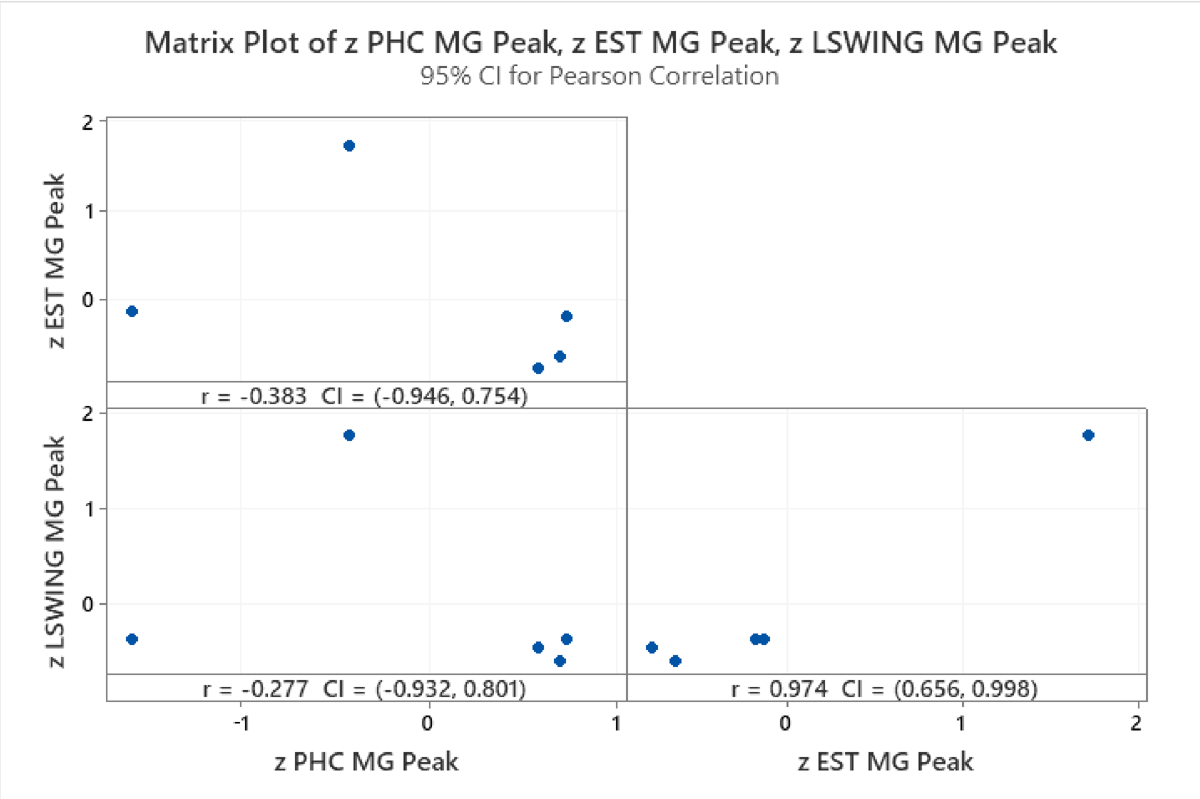

Matrix Plot of z SLID GM Peak, z EST GM Peak, z LSWING GM Peak
95% CI for Pearson Correlation
z EST GM Peak
z LSWING GM Peak
r = -0.708 CI = (-0.979, 0.464)
r = -0.870 CI = (-0.991, 0.053)
r = 0.738 CI = (-0.413, 0.981)
z SLID GM Peak
z EST GM Peak

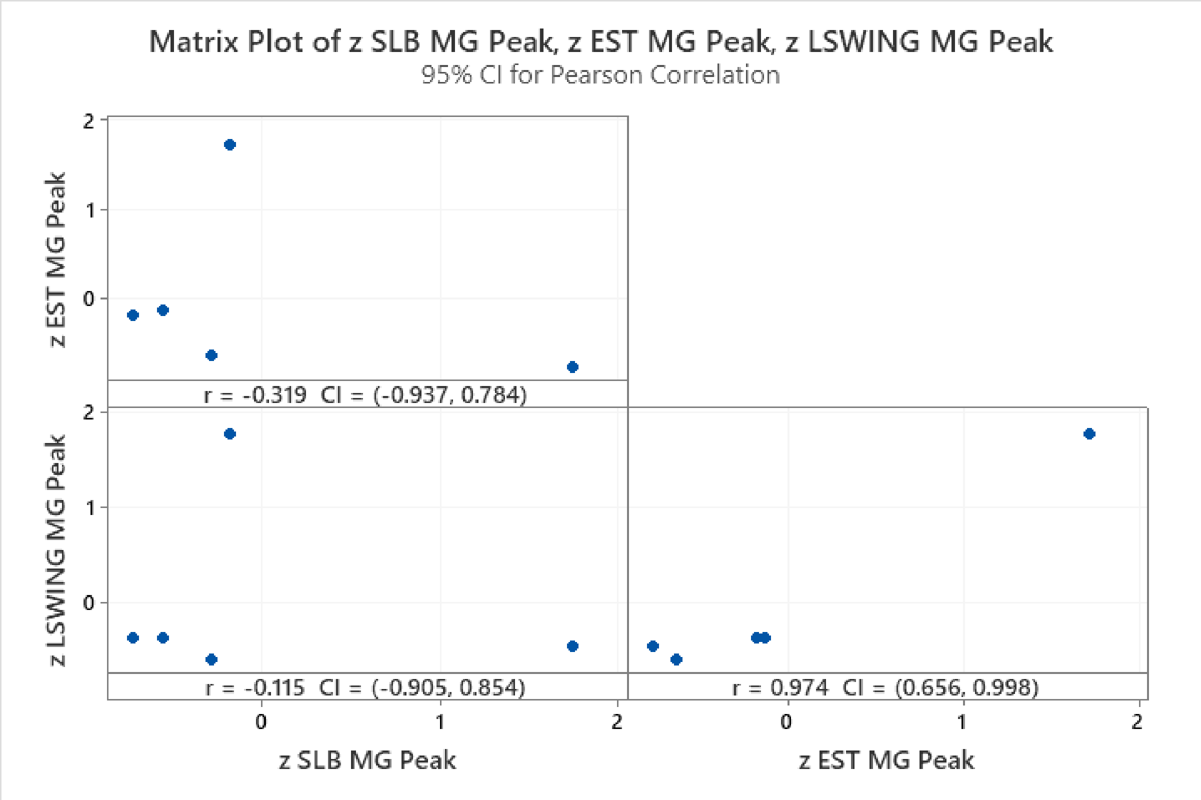

Matrix Plot of z SLRCH_BW GM Peak, z EST GM Peak, z LSWING GM Peak
95% CI for Pearson Correlation
z EST GM Peak
z LSWING GM Peak
r = 0.124 CI = (-0.851, 0.907)
r = 0.264 CI = (-0.806, 0.930)
r = 0.738 CI = (-0.413, 0.981)
z SLRCH_BW GM Peak
z EST GM Peak

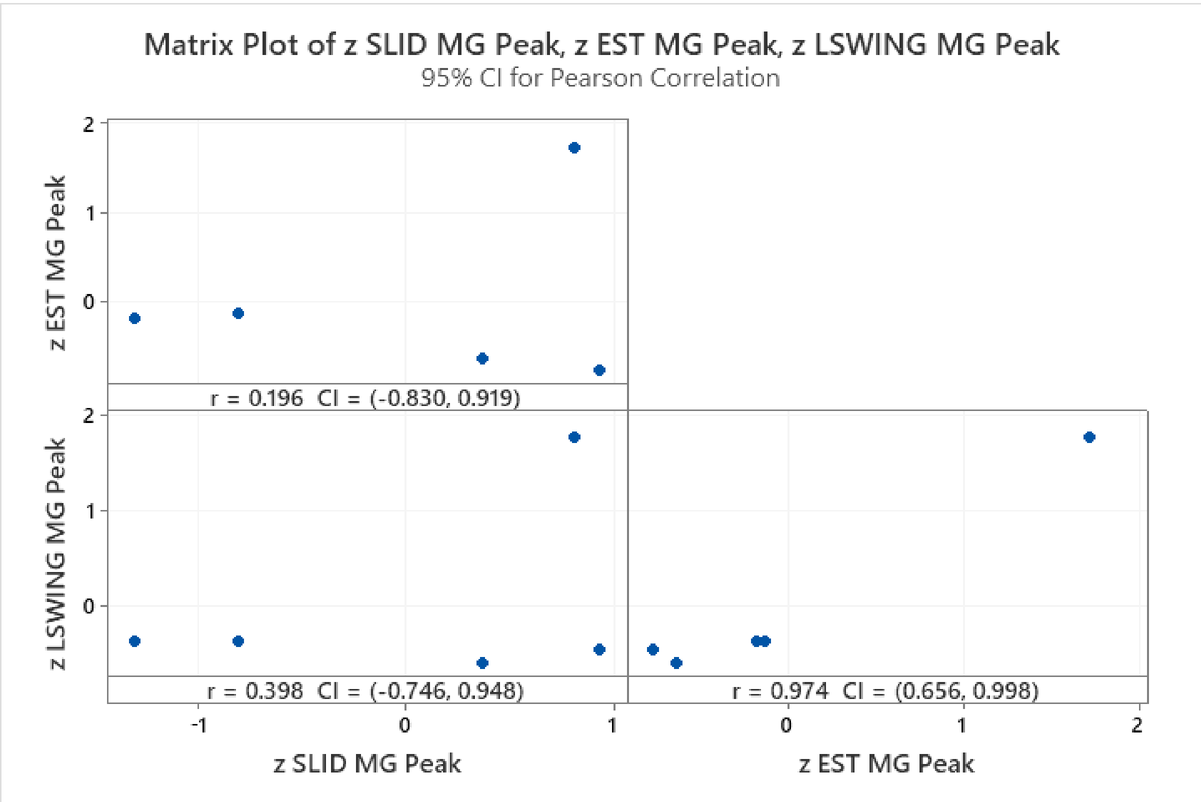

Matrix Plot of z SLRCH_BAR GM Peak, z EST GM Peak, z LSWING GM Peak
95% CI for Pearson Correlation
z EST GM Peak
z LSWING GM Peak
r = 0.575 CI = (-0.624, 0.967)
r = 0.408 CI = (-0.741, 0.949)
r = 0.738 CI = (-0.413, 0.981)
z SLRCH_BAR GM Peak
z EST GM Peak

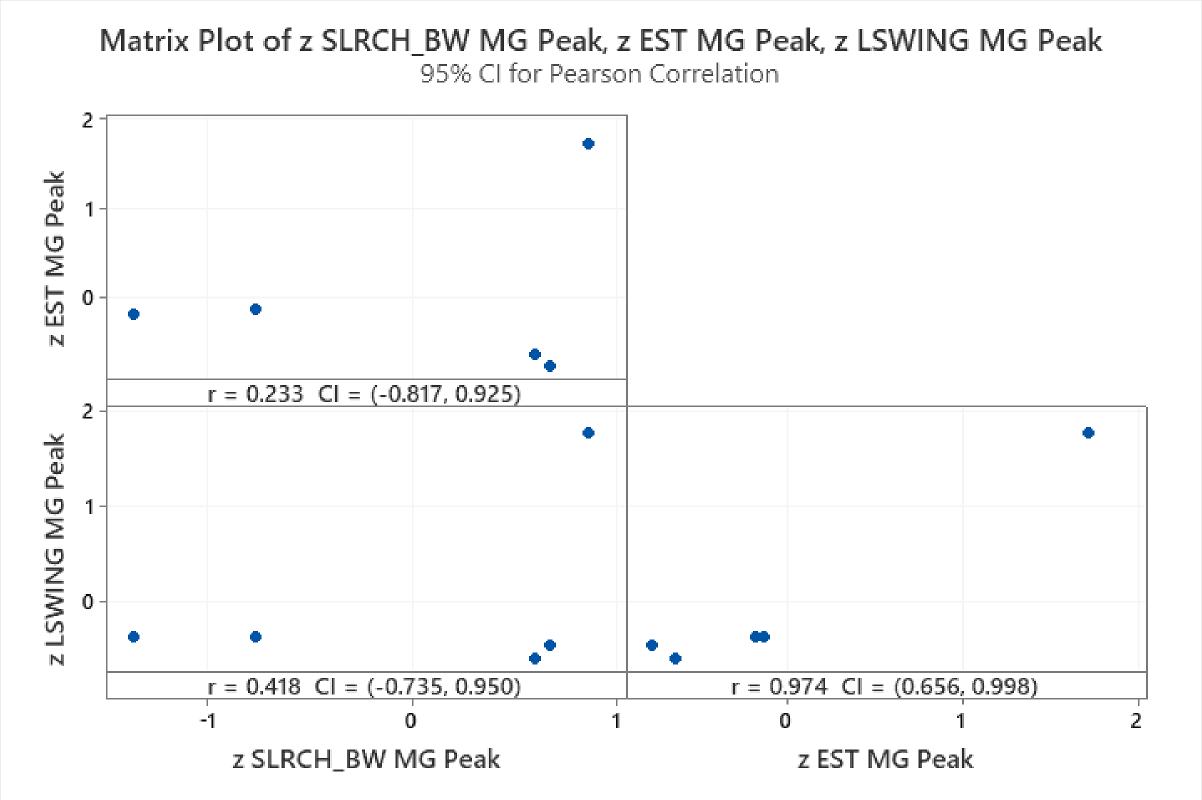
MG scatter plots – Peak nEMG – Sprint phase and individual exercises

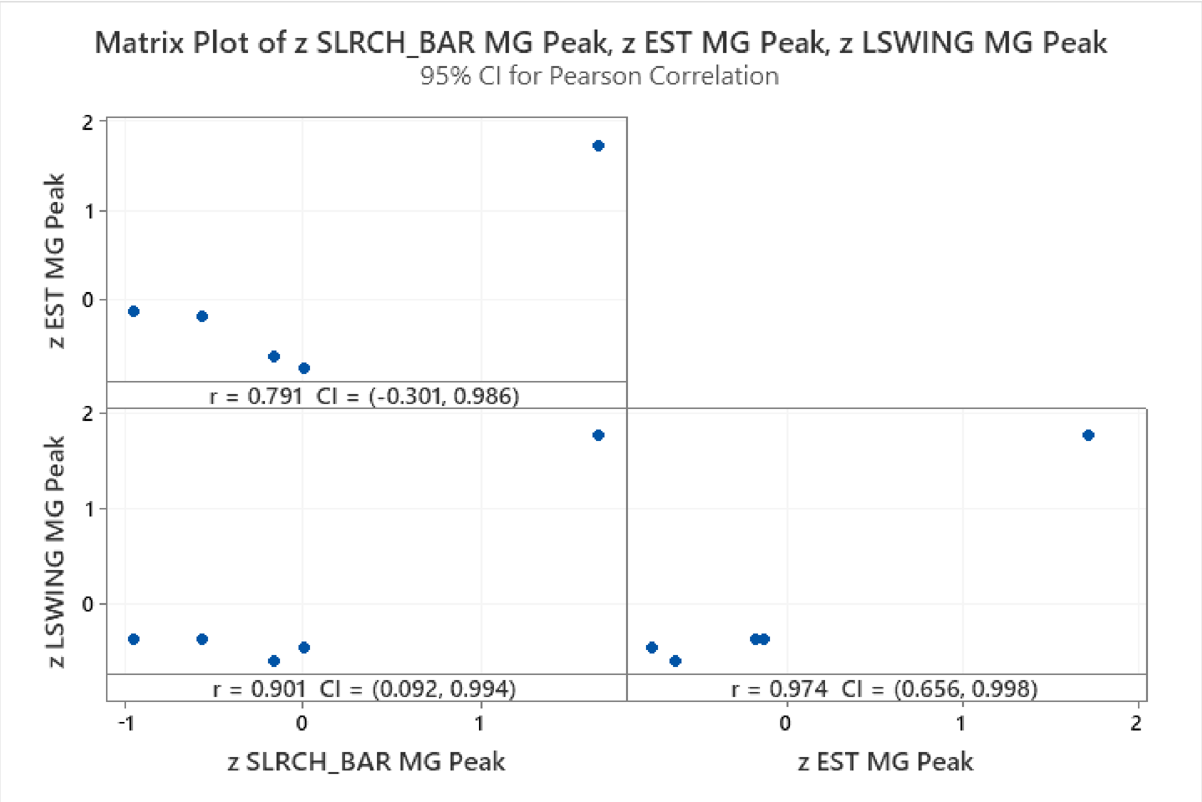





Matrix Plot of z SLB MG Peak, z EST MG Peak, z LSWING MG Peak
95% CI for Pearson Correlation
z EST MG Peak
z LSWING MG Peak
r = -0.319 CI = (-0.937, 0.784)
r = -0.115 CI = (-0.905, 0.854)
r = 0.974 CI = (0.656, 0.998)
z SLB MG Peak
z EST MG Peak

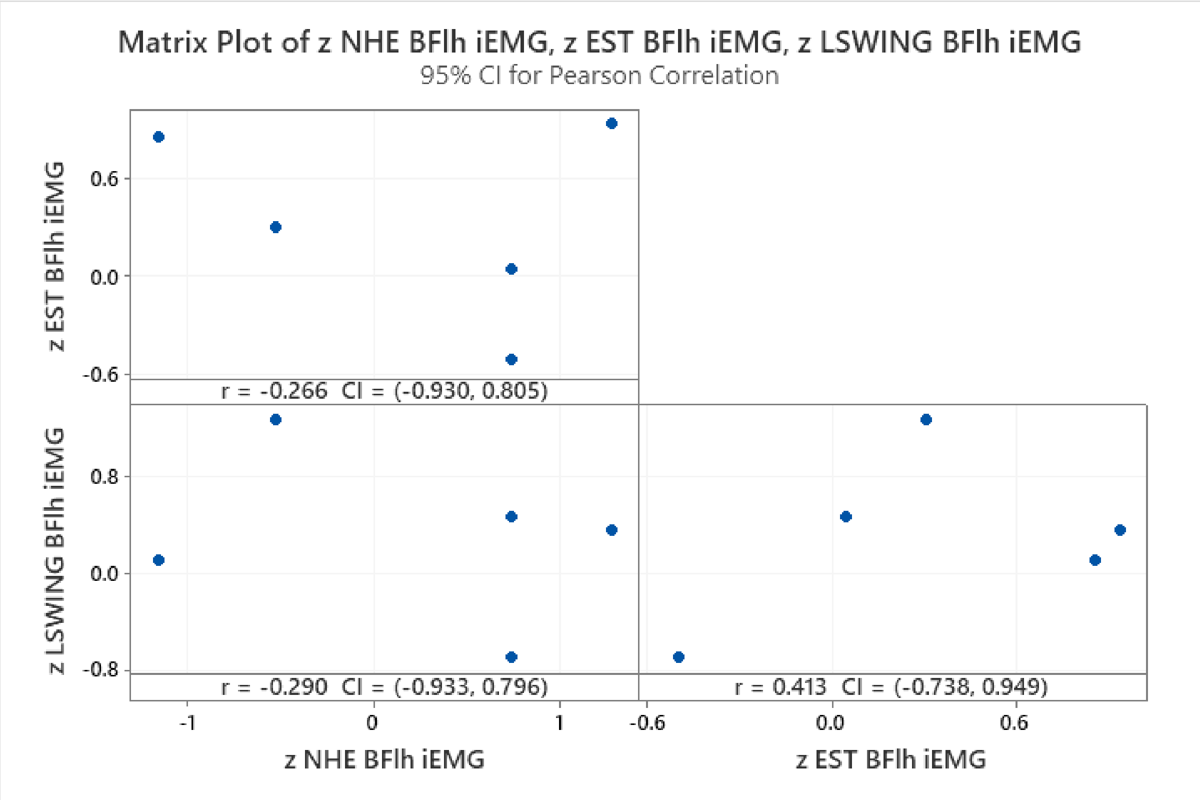

Matrix Plot of z SLID MG Peak, z EST MG Peak, z LSWING MG Peak
95% CI for Pearson Correlation
z EST MG Peak
z LSWING MG Peak
r = 0.196 CI = (-0.830, 0.919)
r = 0.398 CI = (-0.746, 0.948)
r = 0.974 CI = (0.656, 0.998)
z SLID MG Peak
z EST MG Peak

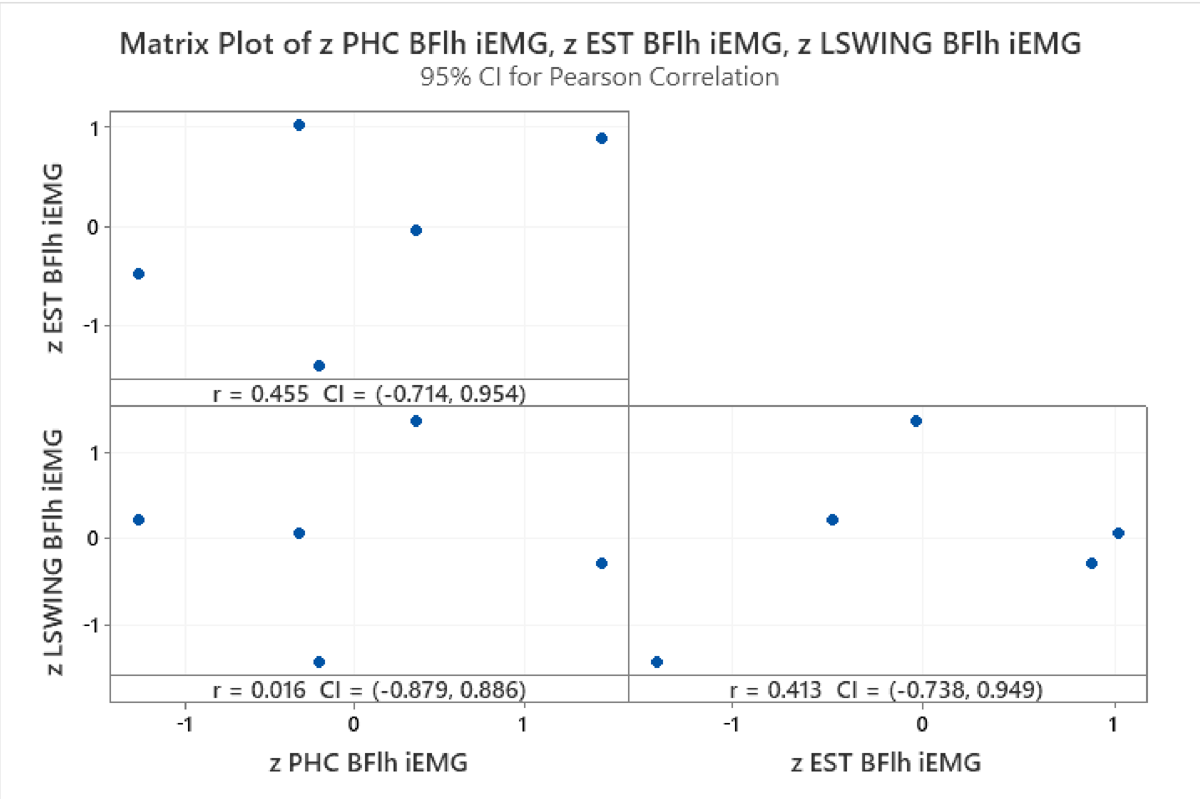

Matrix Plot of z SLRCH_BW MG Peak, z EST MG Peak, z LSWING MG Peak
95% CI for Pearson Correlation
z EST MG Peak
z LSWING MG Peak
r = 0.233 CI = (-0.817, 0.925)
r = 0.418 CI = (-0.735, 0.950)
r = 0.974 CI = (0.656, 0.998)
z SLRCH_BW MG Peak
z EST MG Peak

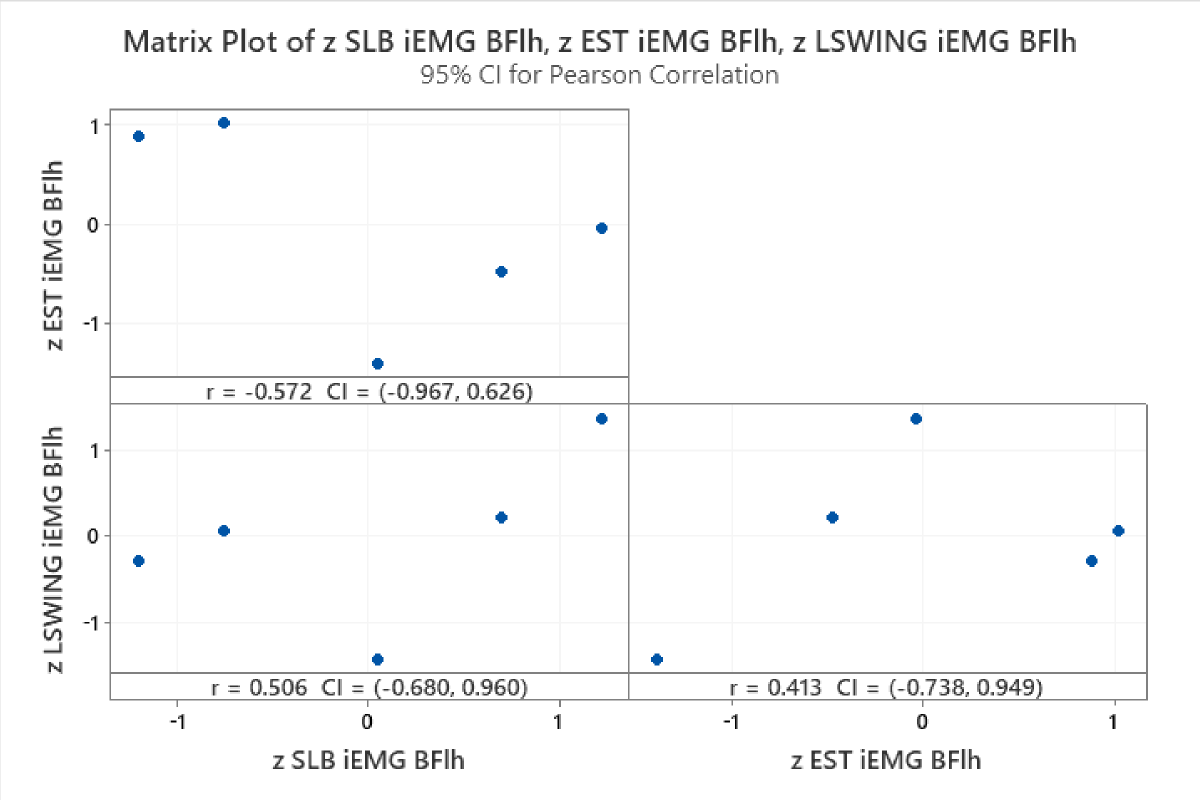

Matrix Plot of z SLRCH_BAR MG Peak, z EST MG Peak, z LSWING MG Peak
95% CI for Pearson Correlation
z EST MG Peak
z LSWING MG Peak
r = 0.791 CI = (-0.301, 0.986)
r = 0.901 CI = (0.092, 0.994)
r = 0.974 CI = (0.656, 0.998)
z SLRCH_BAR MG Peak
z EST MG Peak

APPENDIX 5- SCATTER PLOTS – NORMALISED INTEGRATED EMG (STUDY 3)

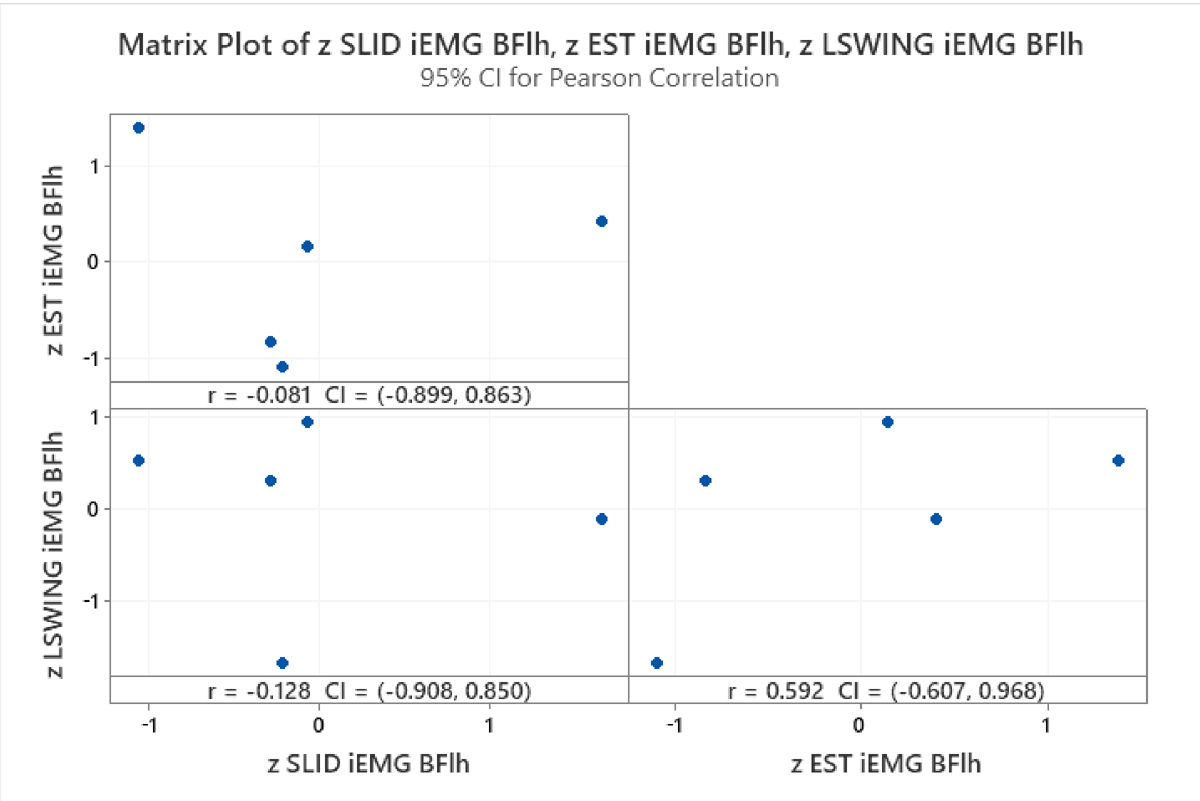
BFlh scatter plots – niEMG – Sprint phase and individual exercises



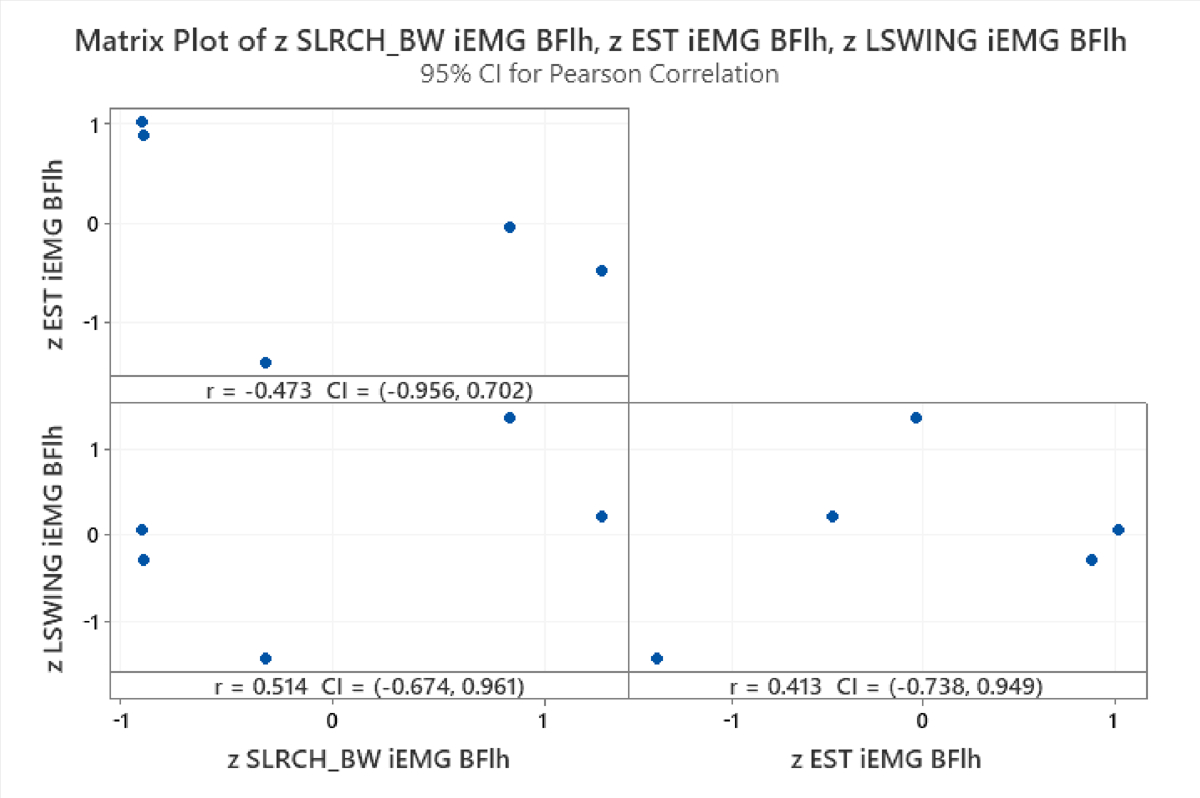




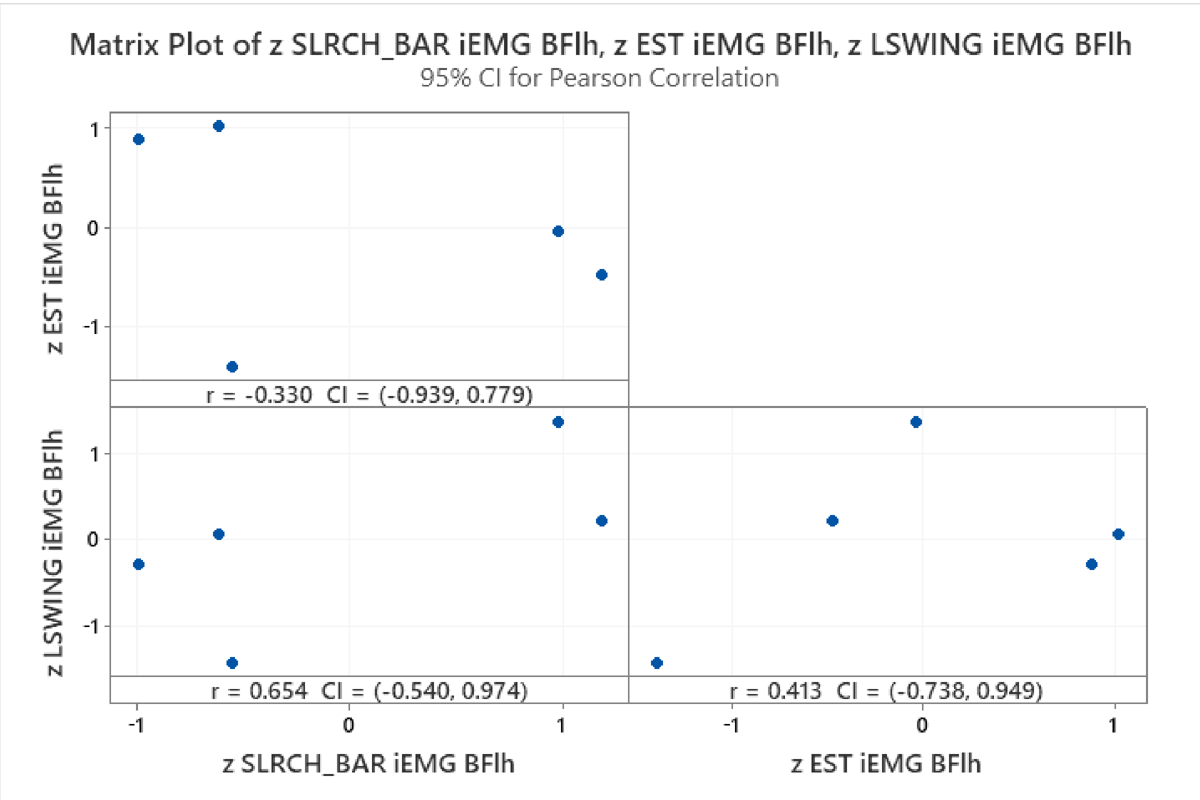
Matrix Plot of z SLB iEMG BFlh, z EST iEMG BFlh, z LSWING iEMG BFlh
95% CI for Pearson Correlation
z EST iEMG BFlh
z LSWING iEMG BFlh
r = -0.572 CI = (-0.967, 0.626)
r = 0.506 CI = (-0.680, 0.960)
r = 0.413 CI = (-0.738, 0.949)
z SLB iEMG BFlh
z EST iEMG BFlh



Matrix Plot of z SLID iEMG BFlh, z EST iEMG BFlh, z LSWING iEMG BFlh
95% CI for Pearson Correlation
z EST iEMG BFlh
z LSWING iEMG BFlh
r = -0.081 CI = (-0.899, 0.863)
r = -0.128 CI = (-0.908, 0.850)
r = 0.592 CI = (-0.607, 0.968)
z SLID iEMG BFlh
z EST iEMG BFlh

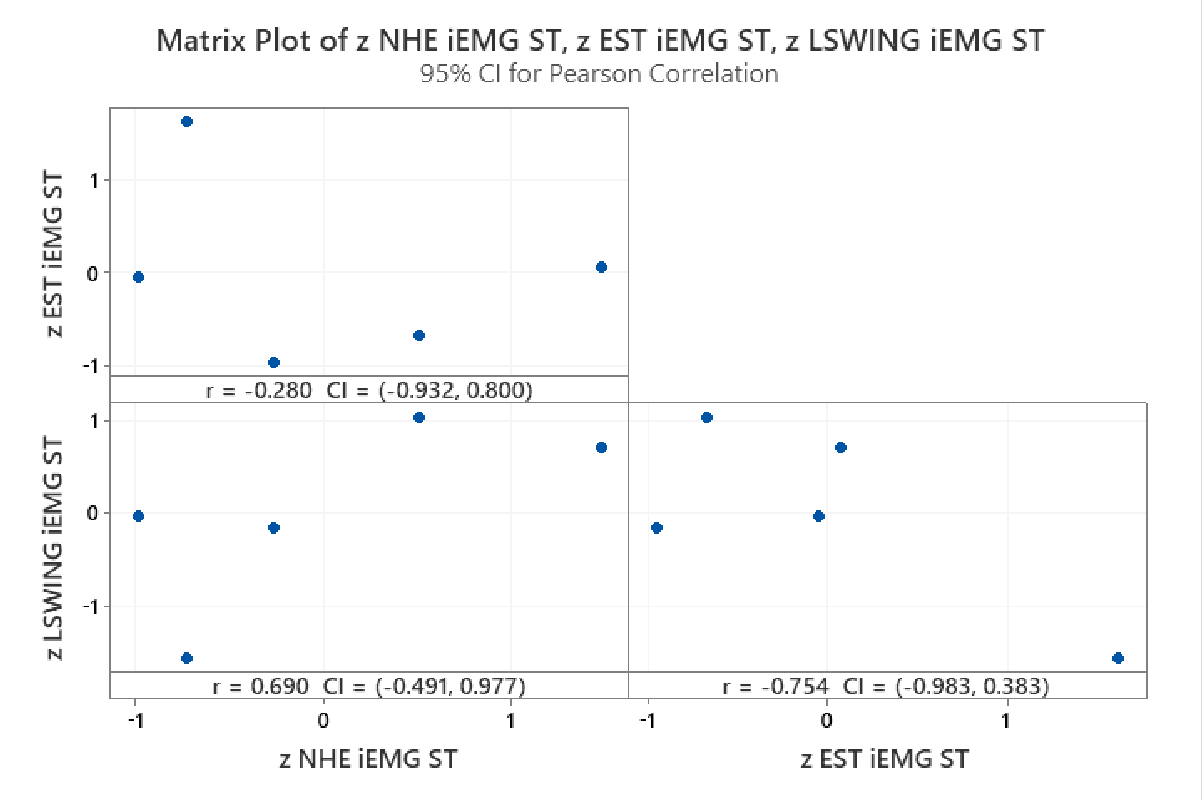


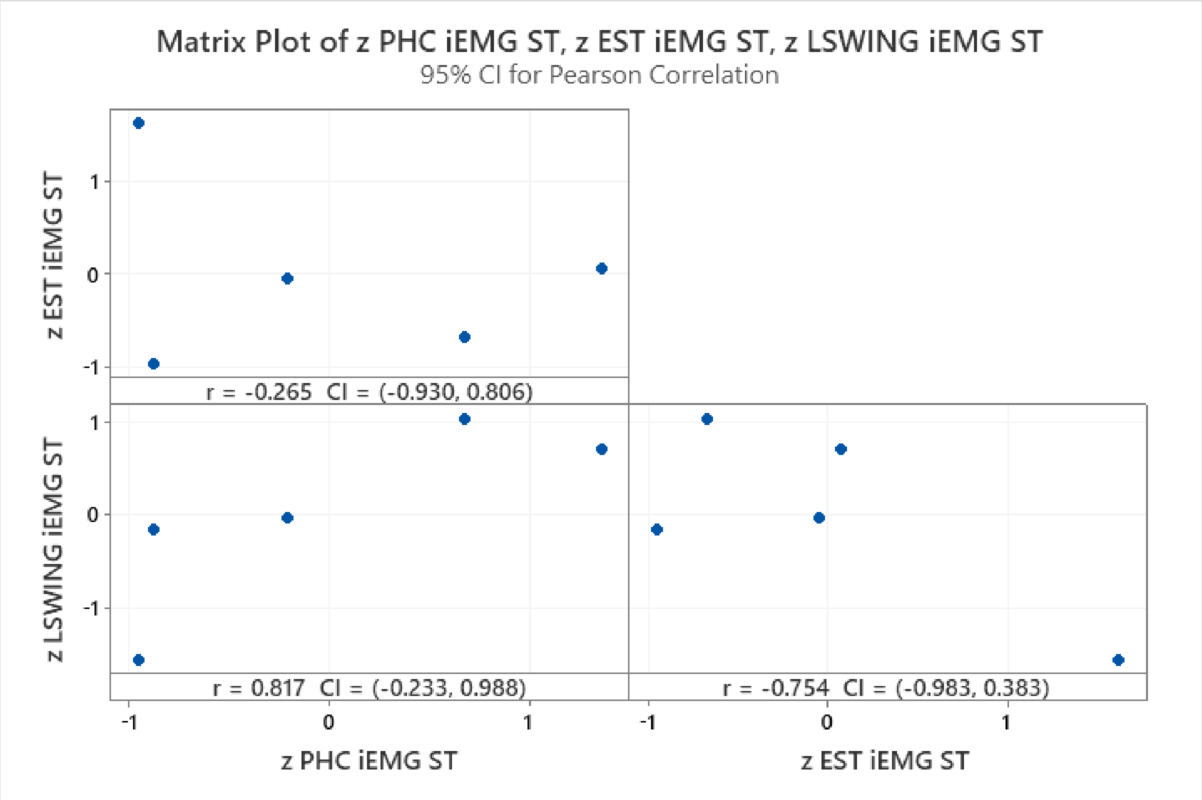
Matrix Plot of z SLRCH_BW iEMG BFlh, z EST iEMG BFlh, z LSWING iEMG BFlh
95% CI for Pearson Correlation
z EST iEMG BFlh
z LSWING iEMG BFlh
r = -0.473 CI = (-0.956, 0.702)
r = 0.514 CI = (-0.674, 0.961)
r = 0.413 CI = (-0.738, 0.949)
z SLRCH_BW iEMG BFlh
z EST iEMG BFlh

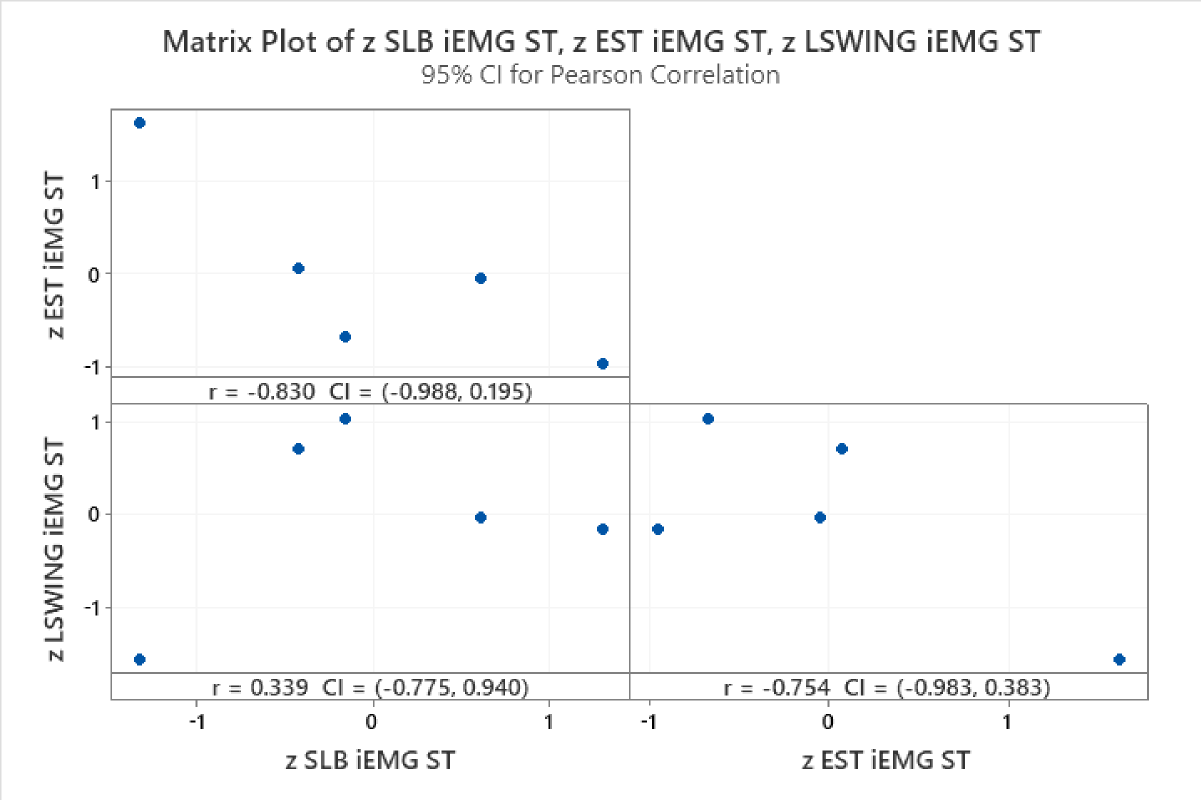


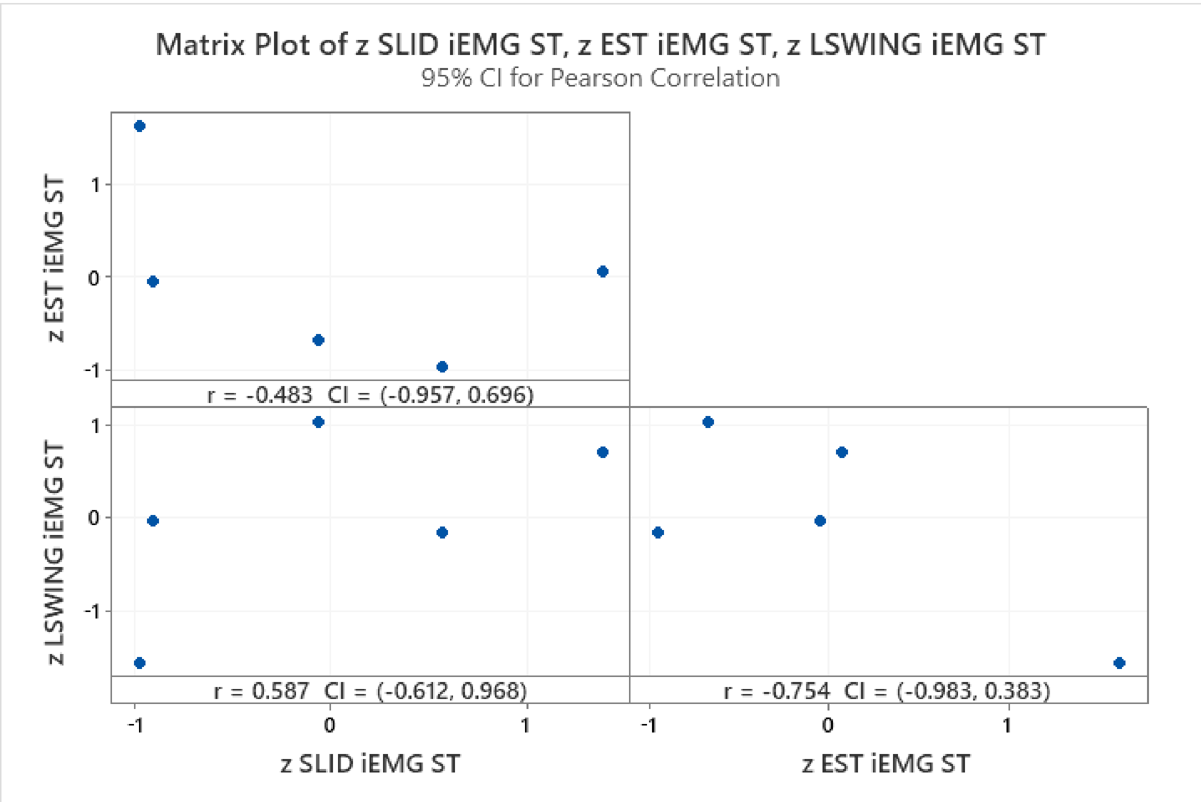
Matrix Plot of z SLRCH_BAR iEMG BFlh, z EST iEMG BFlh, z LSWING iEMG BFlh
95% CI for Pearson Correlation
z EST iEMG BFlh
z LSWING iEMG BFlh
r = -0.330 CI = (-0.939, 0.779)
r = 0.654 CI = (-0.540, 0.974)
r = 0.413 CI = (-0.738, 0.949)
z SLRCH_BAR iEMG BFlh
z EST iEMG BFlh

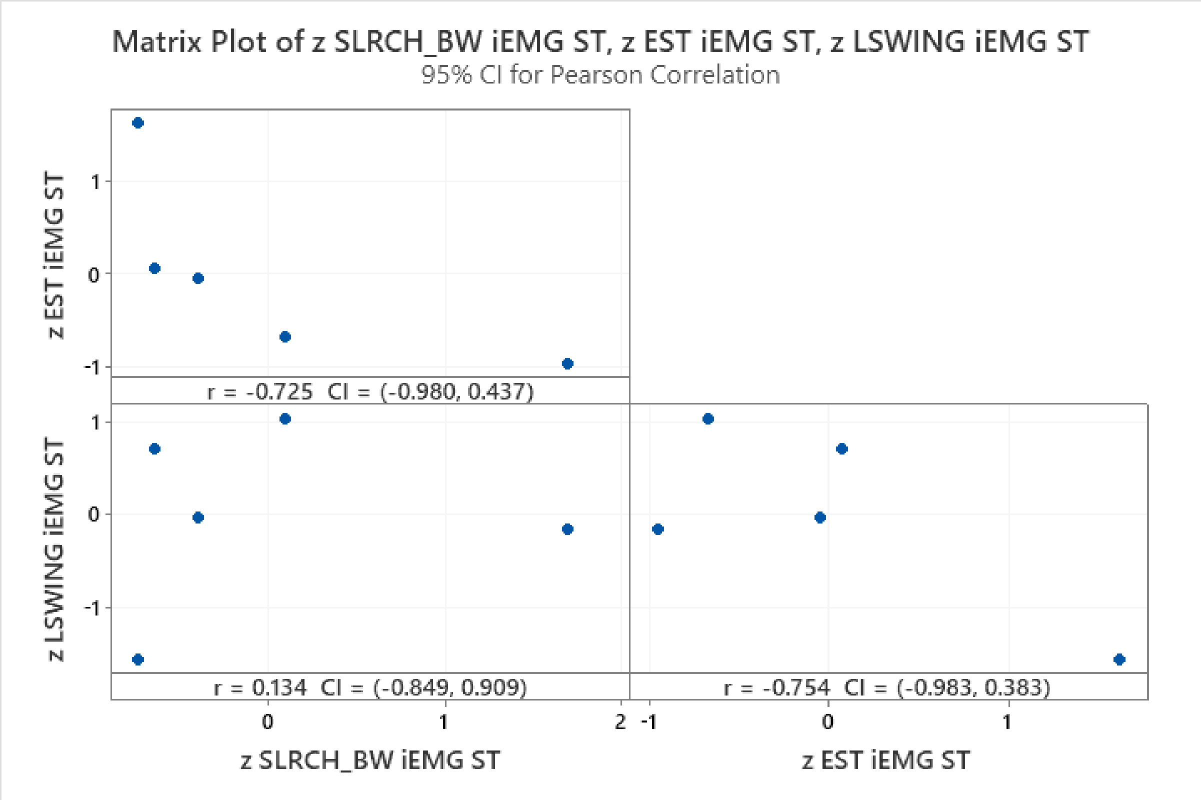
ST scatter plots – niEMG – Sprint phase and individual exercises

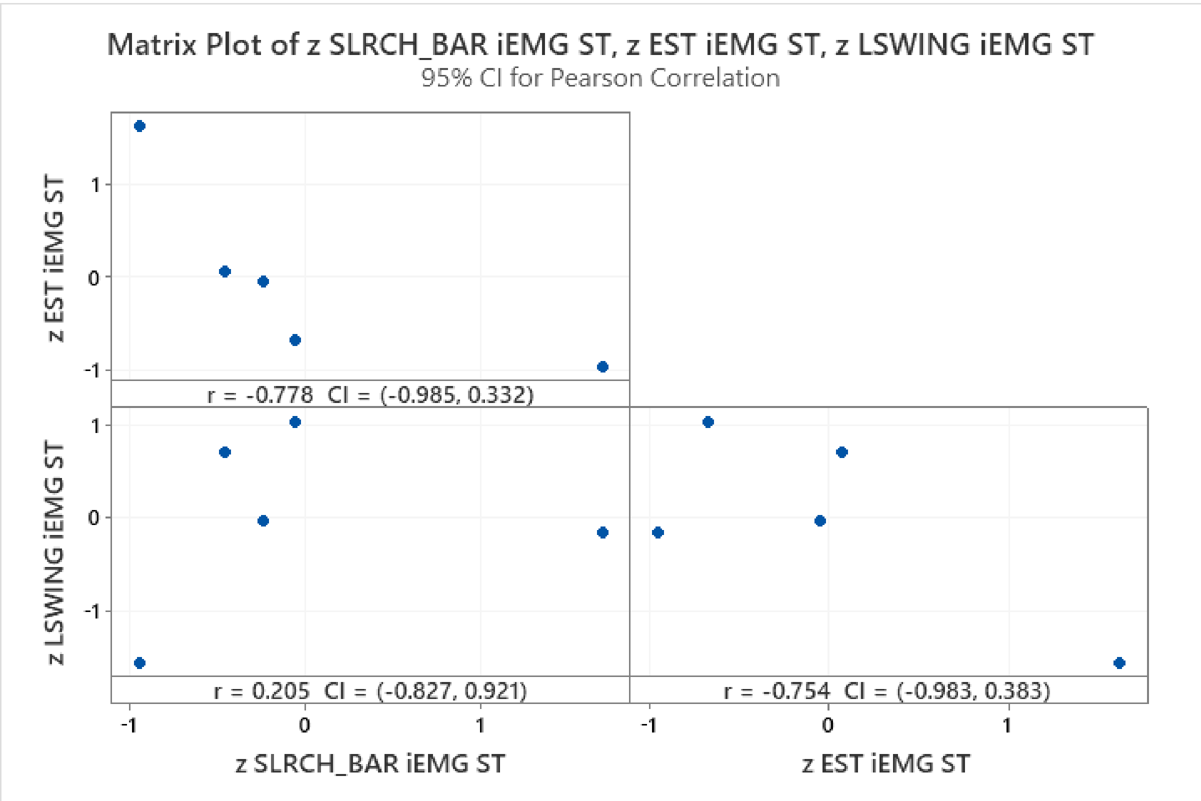




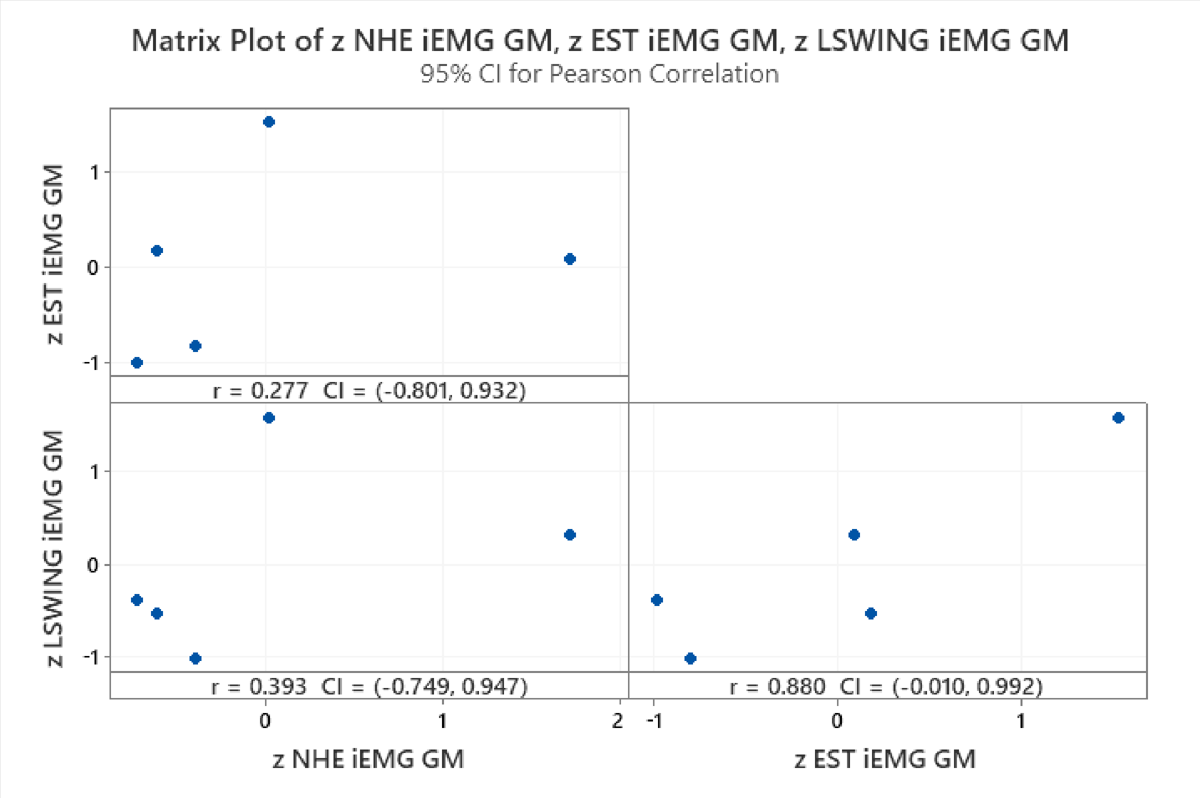

Matrix Plot of z SLB iEMG ST, z EST iEMG ST, z LSWING iEMG ST
95% CI for Pearson Correlation
z EST iEMG ST
z LSWING iEMG ST
r = -0.830 CI = (-0.988, 0.195)
r = 0.339 CI = (-0.775, 0.940)
r = -0.754 CI = (-0.983, 0.383)
z SLB iEMG ST
z EST iEMG ST

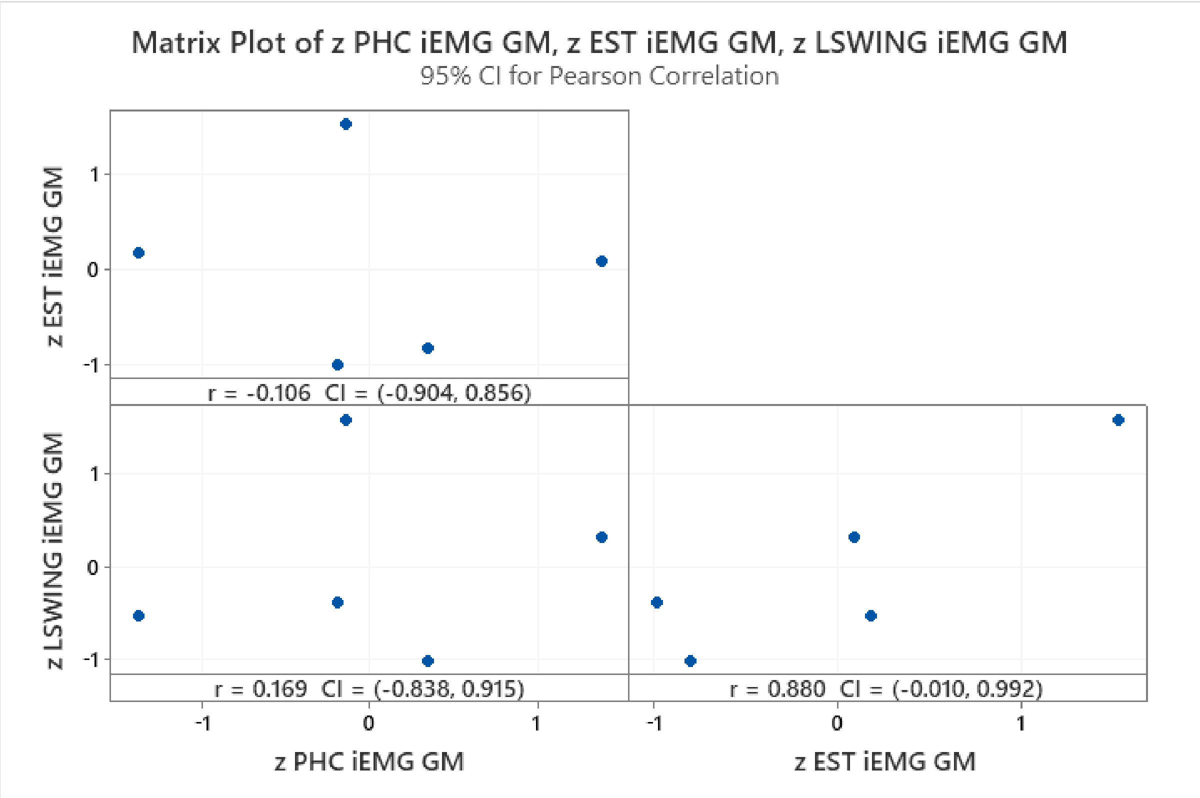

Matrix Plot of z SLID iEMG ST, z EST iEMG ST, z LSWING iEMG ST
95% CI for Pearson Correlation
z EST iEMG ST
z LSWING iEMG ST
r = -0.483 CI = (-0.957, 0.696)
r = 0.587 CI = (-0.612, 0.968)
r = -0.754 CI = (-0.983, 0.383)
z SLID iEMG ST
z EST iEMG ST

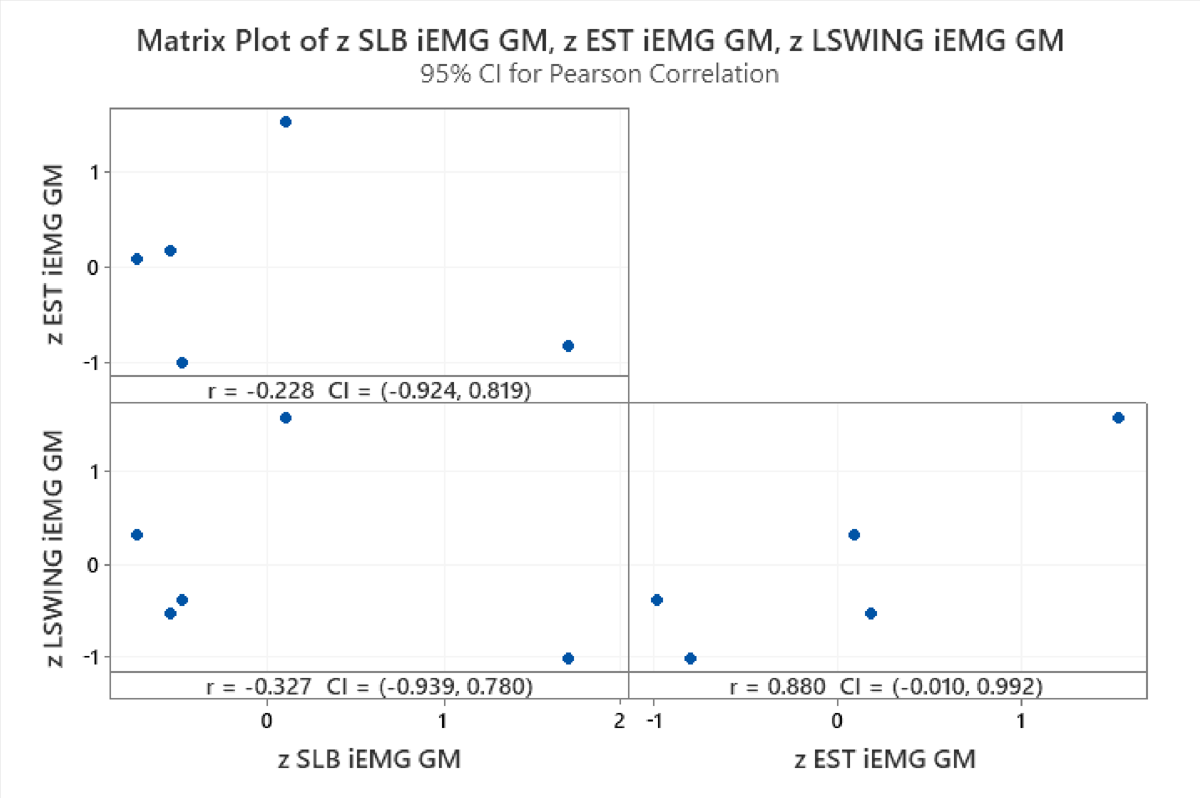

Matrix Plot of z SLRCH_BW iEMG ST, z EST iEMG ST, z LSWING iEMG ST
95% CI for Pearson Correlation
z EST iEMG ST
z LSWING iEMG ST
r = -0.725 CI = (-0.980, 0.437)
r = 0.134 CI = (-0.849, 0.909)
r = -0.754 CI = (-0.983, 0.383)
z SLRCH_BW iEMG ST
z EST iEMG ST

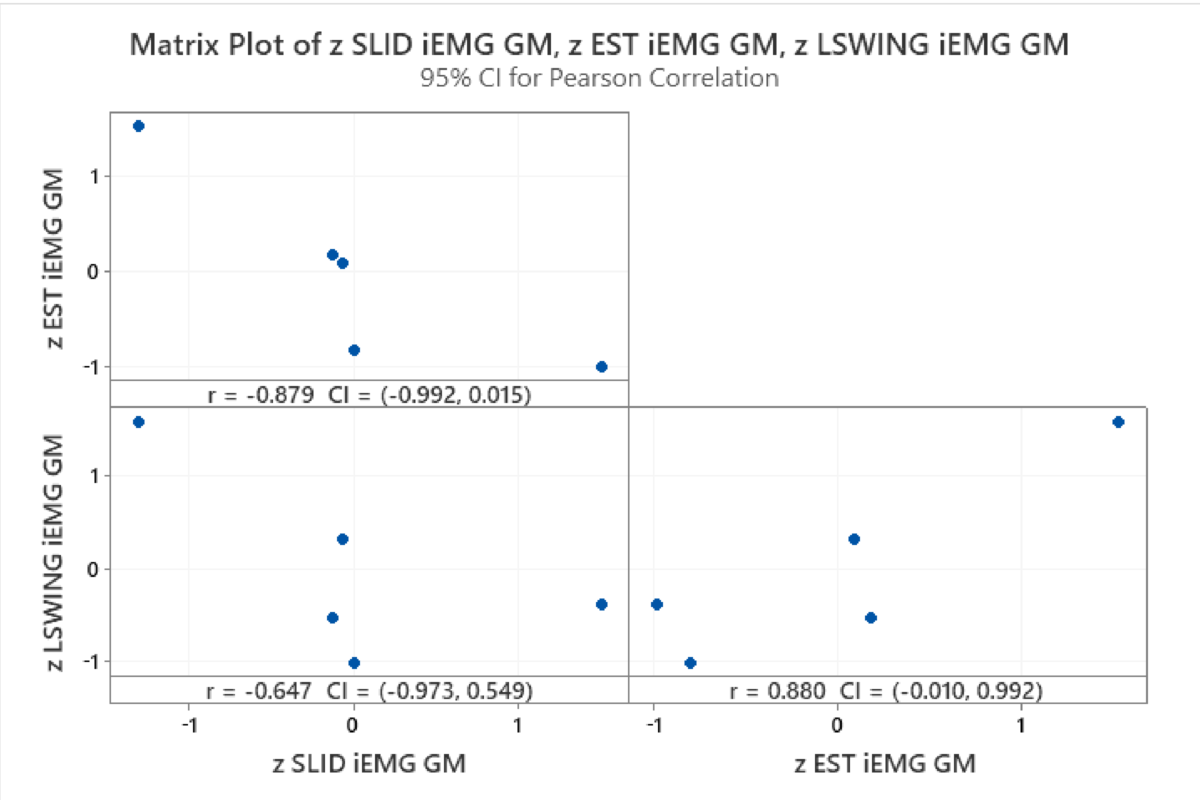

Matrix Plot of z SLRCH_BAR iEMG ST, z EST iEMG ST, z LSWING iEMG ST
95% CI for Pearson Correlation
z EST iEMG ST
z LSWING iEMG ST
r = -0.778 CI = (-0.985, 0.332)
r = 0.205 CI = (-0.827, 0.921)
r = -0.754 CI = (-0.983, 0.383)
z SLRCH_BAR iEMG ST
z EST iEMG ST

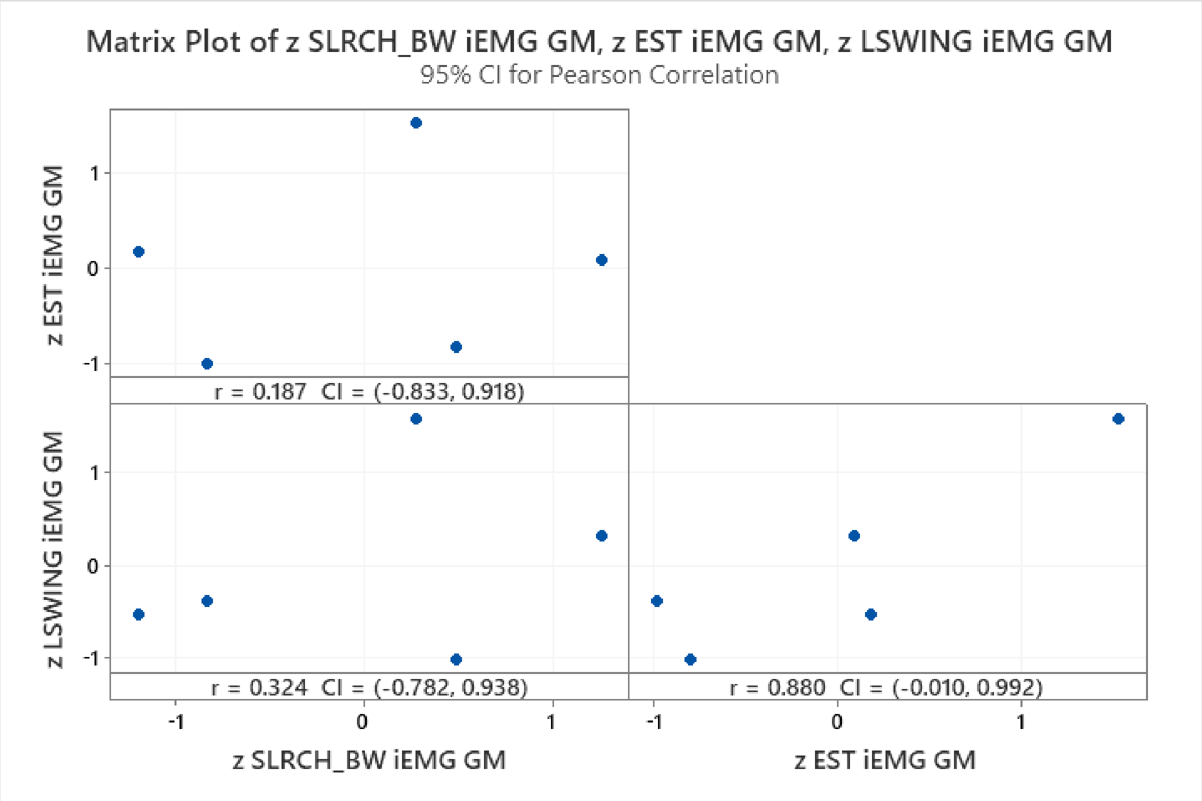
GM scatter plots – niEMG – Sprint phase and individual exercises

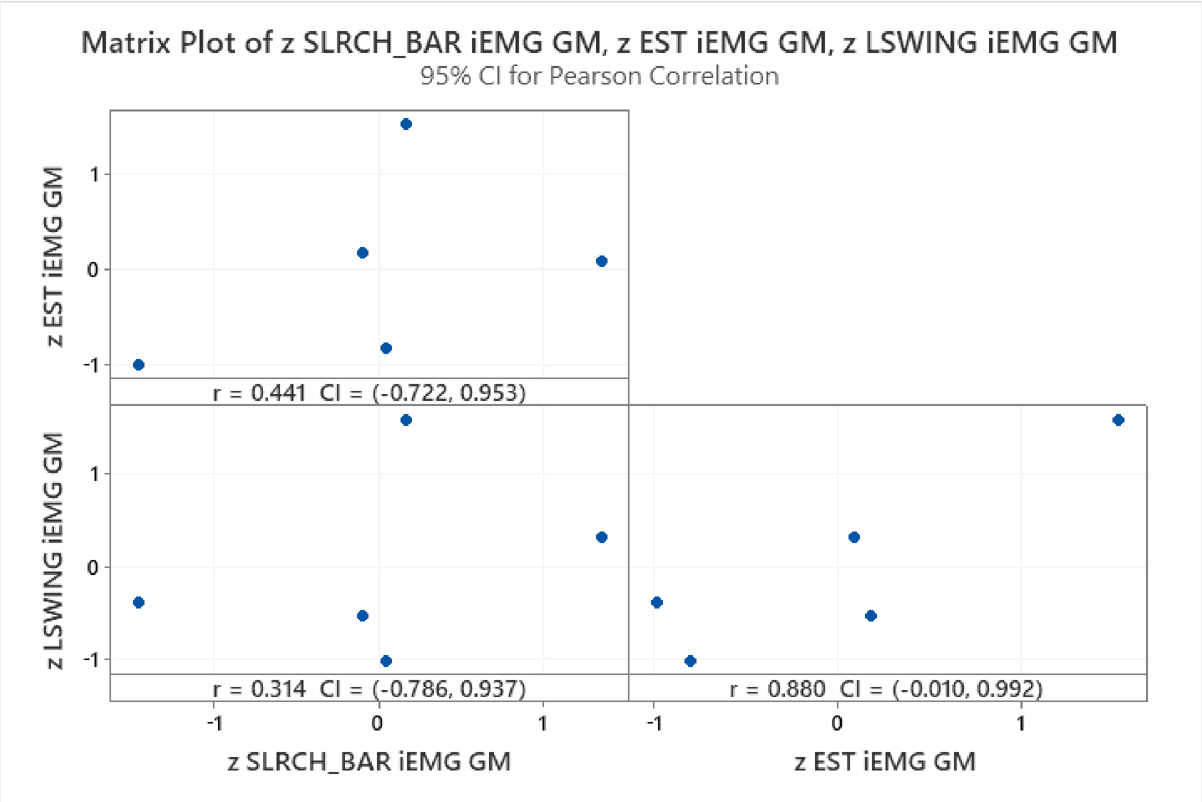




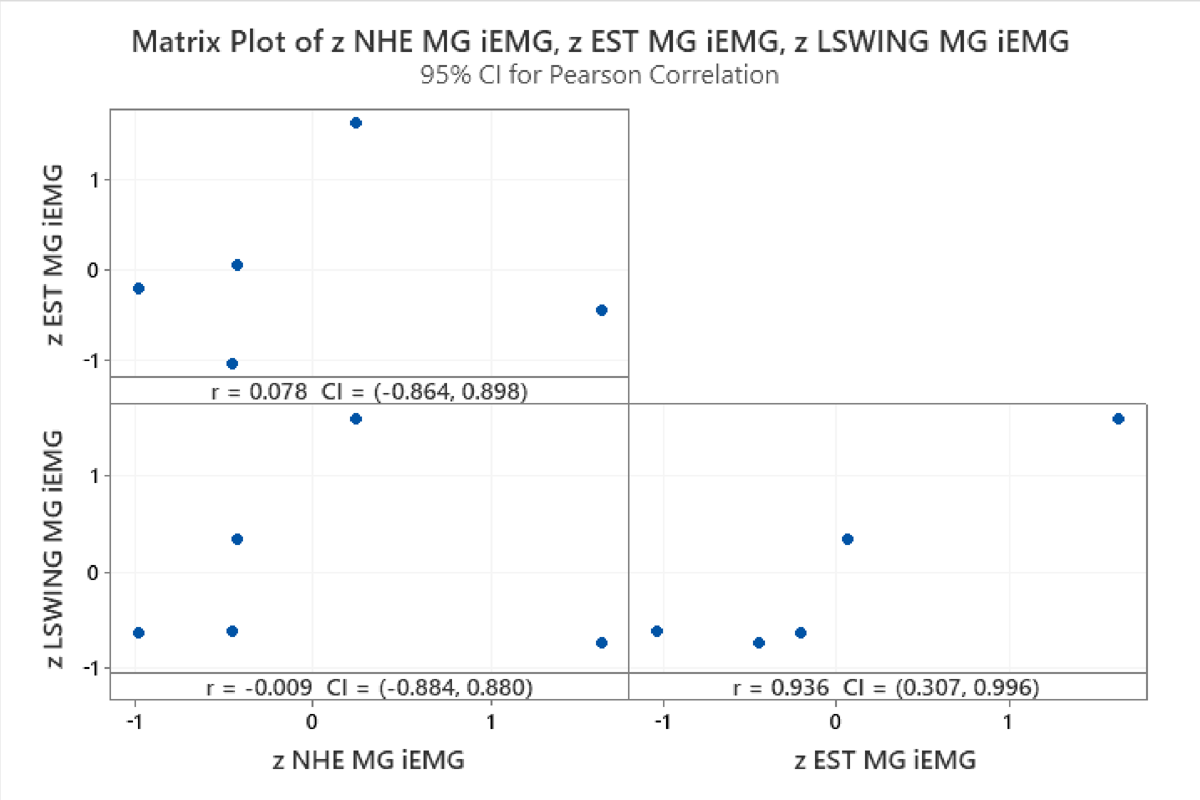

Matrix Plot of z SLB iEMG GM, z EST iEMG GM, z LSWING iEMG GM
95% CI for Pearson Correlation
z EST iEMG GM
z LSWING iEMG GM
r = -0.228 CI = (-0.924, 0.819)
r = -0.327 CI = (-0.939, 0.780)
r = 0.880 CI = (-0.010, 0.992)
z SLB iEMG GM
z EST iEMG GM

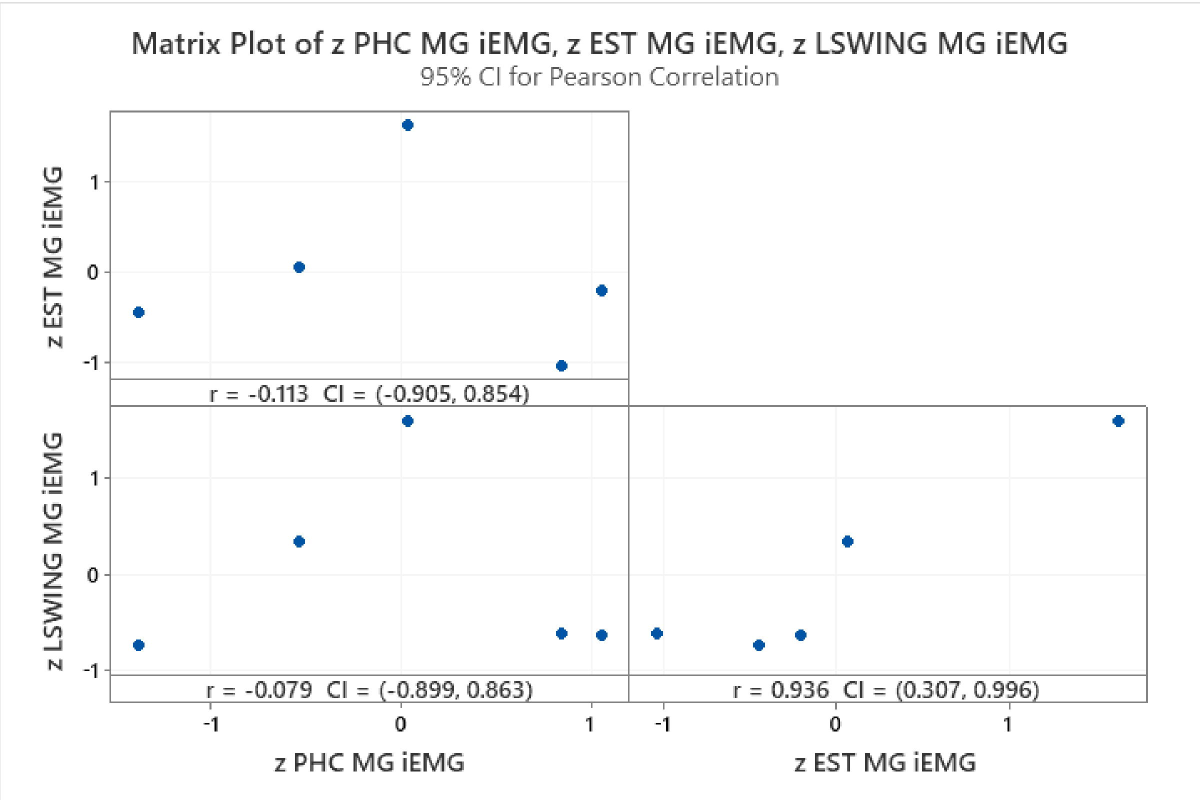

Matrix Plot of z SLID iEMG GM, z EST iEMG GM, z LSWING iEMG GM
95% CI for Pearson Correlation
z EST iEMG GM
z LSWING iEMG GM
r = -0.879 CI = (-0.992, 0.015)
r = -0.647 CI = (-0.973, 0.549)
r = 0.880 CI = (-0.010, 0.992)
z SLID iEMG GM
z EST iEMG GM

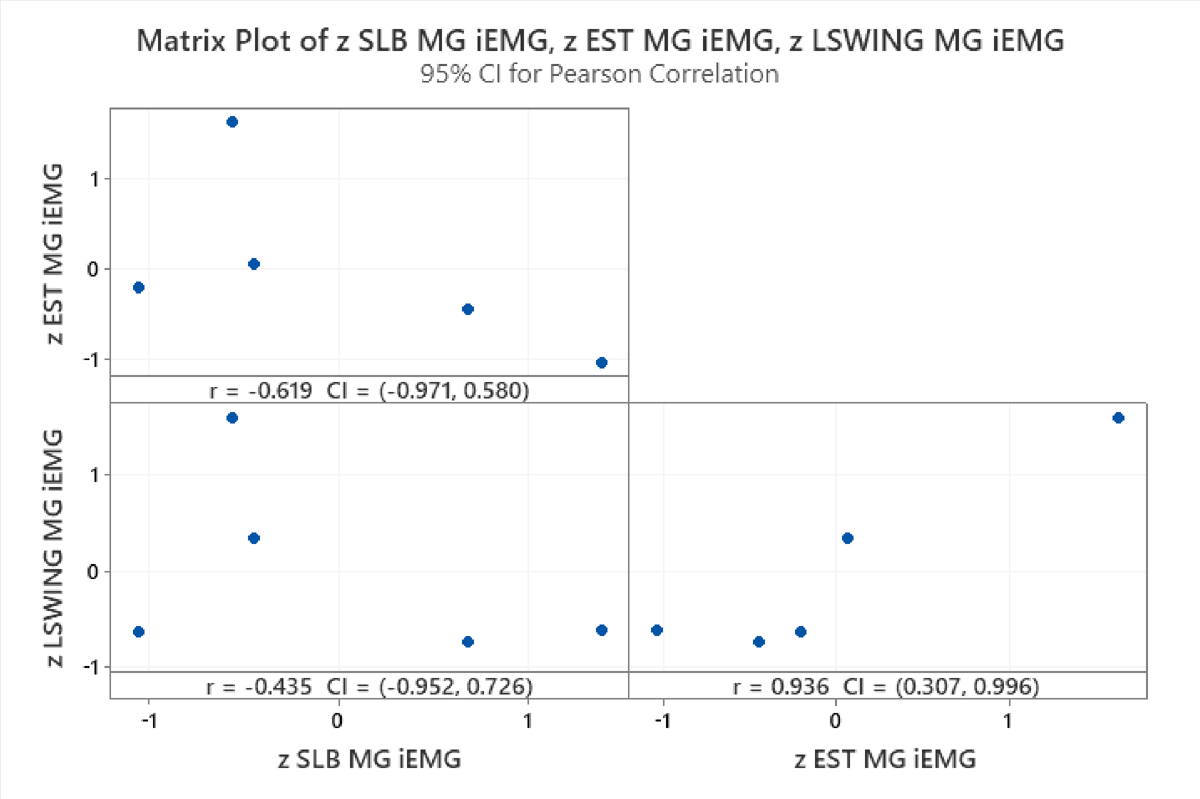

Matrix Plot of z SLRCH_BW iEMG GM, z EST iEMG GM, z LSWING iEMG GM
95% CI for Pearson Correlation
z EST iEMG GM
z LSWING iEMG GM
r = 0.187 CI = (-0.833, 0.918)
r = 0.324 CI = (-0.782, 0.938)
r = 0.880 CI = (-0.010, 0.992)
z SLRCH_BW iEMG GM
z EST iEMG GM

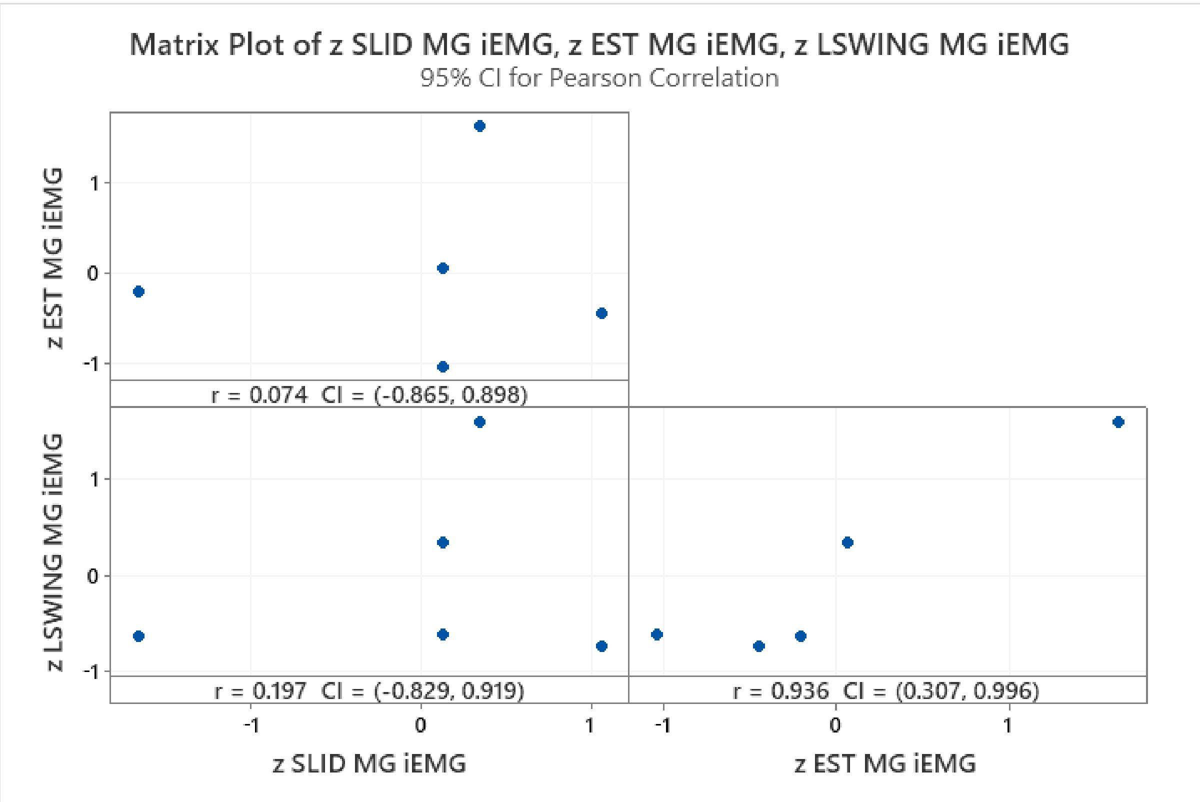

Matrix Plot of z SLRCH_BAR iEMG GM, z EST iEMG GM, z LSWING iEMG GM
95% CI for Pearson Correlation
z EST iEMG GM
z LSWING iEMG GM
r = 0.441 CI = (-0.722, 0.953)
r = 0.314 CI = (-0.786, 0.937)
r = 0.880 CI = (-0.010, 0.992)
z SLRCH_BAR iEMG GM
z EST iEMG GM

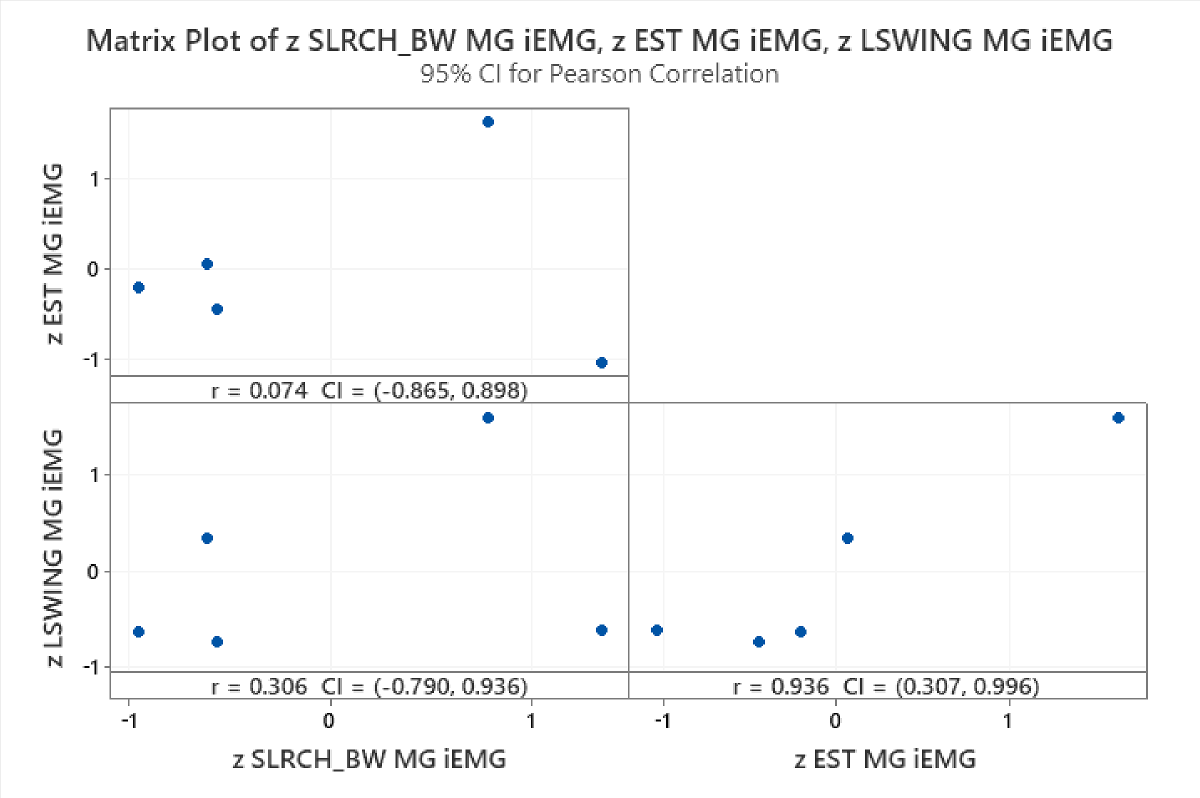
MG scatter plots – niEMG – Sprint phase and individual exercises

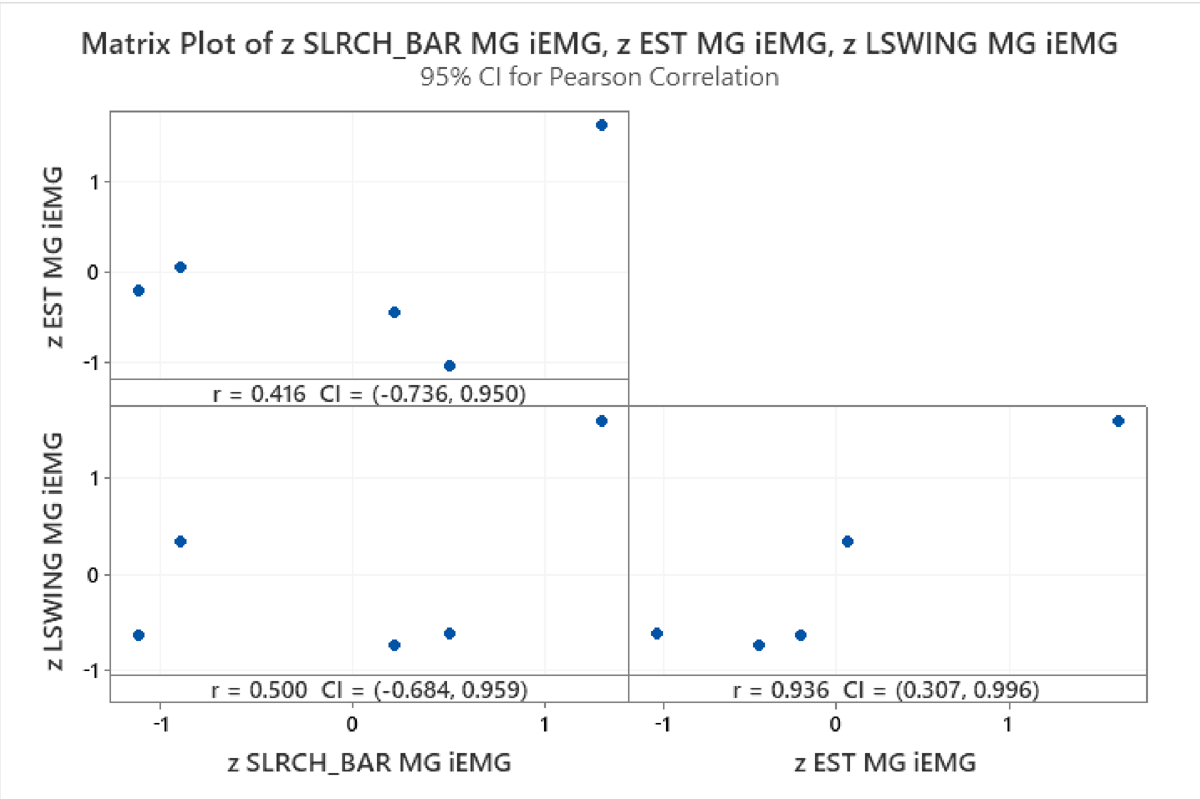





Matrix Plot of z SLB MG iEMG, z EST MG iEMG, z LSWING MG iEMG
95% CI for Pearson Correlation
z EST MG iEMG
z LSWING MG iEMG
r = -0.619 CI = (-0.971, 0.580)
r = -0.435 CI = (-0.952, 0.726)
r = 0.936 CI = (0.307, 0.996)
z SLB MG iEMG
z EST MG iEMG


Matrix Plot of z SLID MG iEMG, z EST MG iEMG, z LSWING MG iEMG
95% CI for Pearson Correlation
z EST MG iEMG
z LSWING MG iEMG
r = 0.074 CI = (-0.865, 0.898)
r = 0.197 CI = (-0.829, 0.919)
r = 0.936 CI = (0.307, 0.996)
z SLID MG iEMG
z EST MG iEMG


Matrix Plot of z SLRCH_BW MG iEMG, z EST MG iEMG, z LSWING MG iEMG
95% CI for Pearson Correlation
z EST MG iEMG
z LSWING MG iEMG
r = 0.074 CI = (-0.865, 0.898)
r = 0.306 CI = (-0.790, 0.936)
r = 0.936 CI = (0.307, 0.996)
z SLRCH_BW MG iEMG
z EST MG iEMG


Matrix Plot of z SLRCH_BAR MG iEMG, z EST MG iEMG, z LSWING MG iEMG
95% CI for Pearson Correlation
z EST MG iEMG
z LSWING MG iEMG
r = 0.416 CI = (-0.736, 0.950)
r = 0.500 CI = (-0.684, 0.959)
r = 0.936 CI = (0.307, 0.996)
z SLRCH_BAR MG iEMG
z EST MG iEMG

APPENDIX 6 – ETHICS FORM (STUDY 4)

When undertaking a research or innovation project, Cardiff Met staff and students are obliged to complete this form in order that the ethics implications of that project may be considered.

The document ***Ethics application guidance notes*** will help you complete this form and is available from the Ethics Governance Section of the Cardiff Met website. The School or Unit in which you are based may also have produced some guidance documents which you can access via your supervisor or School Ethics Coordinator.

PLEASE NOTE:
Participant recruitment or data collection MUST NOT commence until ethics approval has been obtained.

PART ONE

1A: GENERAL INFORMATION	
Name of applicant:	Adeline Miles
Supervisor (if student project):	Dr Isabel Moore
School / Unit:	Sport and Health Sciences
Student number (if applicable):	20075616
Programme enrolled on (if applicable):	PhD Sport
Project Title:	The effect of load on hamstring muscle activity and lower limb kinematics during hamstring training exercises
Expected start date of data collection:	11/07/2021
Approximate duration of data collection:	12 weeks
Funding Body (if applicable):	N/A
Other researcher(s) working on the project:	Professor Jon Oliver
Will the study involve NHS patients or staff?	No
Will the study involve human samples and/or human cell lines?	No

1B: Does your project fall entirely within one of the following categories:	
Desk based, involving only documents and not involving the collection of data from participants	No
Laboratory based, not involving human participants, human samples, animals or animal derived material	No
Practice based not involving human participants (eg curatorial, practice audit)	No
Answering **YES** to any of these questions indicates that the project does not include any participants and you will not therefore be collecting participant data. If this is the case, please provide a short (150 words) non-technical summary of the project, complete the	

Declaration at the bottom of the form and forward this form to your School Ethics Committee (or equivalent). No further information regarding your project is required and you do not need to complete any more sections of this form. If you have answered **NO** to all of these questions, please proceed to 1C.
Non-technical summary of the project:

1C: Does your project fall entirely within one of the following categories:	
Compulsory projects in professional practice (eg Initial Teacher Education)	No
A project for which NHS approval has been obtained NB If this is the case, please ensure that you submit copies of the following with this form: • any questionnaires to be used • participant consent / asset form and withdrawal form • participant information sheets	No
A project which is not compulsory in professional practice and has gained external ethics approval from a body other than the NHS. NB If this is the case, please ensure that you submit a copy of the approved ethics application with this form.	No
If you have answered **YES** to any of these questions, please provide a short (150 words) non-technical summary of the project and **complete the rest of Part One of this form**. You do not need to complete Part Two. Forward your completed form, along with any additional documents required (as indicated above) to your School Ethics Committee (or equivalent). If you have answered **NO** to all of these questions, please complete the rest of this form including Part Two.	
Non-technical summary of the project:	

1D: DATA COLLECTION AND STORAGE
What types of data will you collect or create?
• Raw video data files • Raw electromyographic data files • Analysed electromyographic data inputted into an excel spreadsheet • Coordinate data using motion analysis • Sprint times inputted into an excel spreadsheet • Participant email addresses
How will you manage access to and security of the data?
• All of the data collected will be stored remotely on OneDrive and only the research team will have access to it • Participants will be given a unique identification (ID) code at the start of the study, and all data collected for each participant will be stored using this code • The email addresses, names and ID codes for all participants will be entered into an excel spreadsheet which will be password protected. This password will only be given to the research team and the document will be stored on OneDrive and only be accessible by the research team

Will the data collected be subject to the data retention protocols of any of the following bodies? • Human Tissue Authority (HTA) • Health and Care Research Wales (HCRW) • Applications involving the NHS which will be submitted via IRAS
Yes ☐ For any project which is subject to the data retention protocols of an external body listed, you must develop a data storage plan to be submitted alongside this document for consideration by your School or Unit Ethics Panel.
No ☒ Please confirm that the data collected will be stored in a manner which complies with Cardiff Met requirements via one of the following statements.

STATEMENT 1: FOR STUDENTS ON TAUGHT COURSES I confirm that any non-anonymised data related to research participants will only be stored on OneDrive and that all data held elsewhere will be deleted, unless it is anonymised.	☐
STATEMENT 2: FOR STAFF APPLYING ON BEHALF OF STUDENTS ON TAUGHT COURSES I confirm that all students covered by this application are aware of their obligation to ensure that non-anonymised data related to research participants must only be stored on their Cardiff Met student OneDrive account and that all data held elsewhere must be deleted, unless it is anonymised.	☐
STATEMENT 3: FOR RESEARCH STUDENTS AND STAFF I confirm that any non-anonymised data related to research participants will be stored in a secure manner (using a platform such as OneDrive or FigShare) and that all data held elsewhere will be deleted unless it is anonymised.	☒

DECLARATION: **I confirm that this project conforms with the Cardiff Met Research Integrity & Governance Framework** **I confirm that I will abide by the Cardiff Met requirements regarding confidentiality and anonymity when conducting this project.** **STUDENTS: I confirm that I will not disclose any information about this project without the prior approval of my supervisor.**	
Signature of the applicant:	**Date:** 15th June 2021
FOR STUDENT PROJECTS ONLY	
Name of supervisor: Isabel Moore	**Date:** 16th June 2021
Signature of supervisor:	

Research Ethics Committee use only	
Decision reached: Click here to enter text.	
Project reference number: **PGR-4253**	
Name: Click here to enter text.	Date: Click here to enter a date.
Details of any conditions upon which approval is dependant: Click here to enter text.	

PART TWO

If you haven't already done so elsewhere on this form, in the box below, provide a short (150 words), non-technical summary of the project.	
Hamstring strain injuries are common in sports which involve high-speed running and have a relatively high re-injury occurrence. Due to the susceptibility for injury and re-injury, the hamstring group is of specific interest as injuries can result in a substantial amount of time out of play and create a financial burden on teams. High-speed running is described as the common cause of hamstring injury. The aim of this study is to analyse the effect of load on hamstring muscle activation during exercises that are correlated to muscle activity observed during high-speed running as a means of addressing exercise specificity for hamstring injury prevention. Surface electromyography (sEMG) will be used to record the activity of four lower limb muscles during three x 40 m sprints and three different hamstring exercises using three different loads.	
A RESEARCH DESIGN	
A1 Will you be using an approved protocol in your project?	Yes
A2 If yes, please state the name and code of the approved protocol to be used[2]	
Motion analysis and kinetic measurement of sports and exercise related movements and techniques. Code: 16/10/01L	
A3 Describe the research design to be used in your project	
Participants Participants for the proposed study will be male rugby players (18 – 25 years old) from the Cardiff Metropolitan University 1st team. Participants must take part in regular training (minimum of 45 minutes x 3 times per week), have no history of lower limb injury in the last 12 months and have no history of lower limb surgery. The purpose and nature of the study has been discussed with the rugby coach and he has confirmed that the players can be approached to give them the opportunity to take part in the study (Appendix A). A sample size of 33 has been determined using a sample size calculation (G* Power software, version 3.1.9.7) with a significance value of 0.05 and desired power of 0.80. Data loss experience **Recruitment of participants** Following discussions with the rugby coach and players, the principal investigator will send an information sheet explaining the procedures and scope of the study to the players via email (Appendix B). The contact details for the participants will be acquired from the rugby coach who will get verbal consent from the players to confirm that they are happy to be contacted by the principal investigator via email. Upon agreeing to take part, all participants will be sent a COVID-19 symptom check questionnaire (Appendix C) via email and will be asked to complete this on the	

[2] An Approved Protocol is one which has been approved by Cardiff Met to be used under supervision of designated members of staff. For details of protocols in use in your School or Unit, contact your Ethics Coordinator

morning of the familiarisation process and the day of testing, prior to arriving at NIAC. All participants will be asked to provide written informed consent (Appendix D) prior to any visit to NIAC and will also be provided with a withdrawal of consent form (Appendix E) enabling them to withdraw from the study at any time. Prior to taking part in the data collection process, all participants will complete a PAR-Q to ensure they can take part in the study (Appendix F) – this questionnaire will be sent to participants via email.

Testing Procedures

All data collection will take place in the National Indoor Athletics Centre (NIAC) at the School of Sport and Health Sciences, Cardiff Metropolitan University. Each participant will need to attend NIAC twice and will provide written informed consent prior to their first visit. The first visit will involve participants completing a familiarisation process of the sprinting and exercise protocol a week before data collection. During this process the sprint trials and hamstring exercises will be explained, and each participant will have the opportunity to practice them. All participants will be required to rest from training for 48 hours prior to their second visit to NIAC for data collection to minimise the potential impact of fatigue on test performance. During their second visit to NIAC, the height and body mass of the participants will be recorded and then they will complete a standardised 15-minute warm-up prior to any data being collected. This will be led by the main researcher and will involve dynamic exercises, three 40 m sprints of progressive intensity (70%, 80% and 90%) and dynamic stretching of the main lower limb muscle groups. After completing the warm-up participants will complete three x 40 m sprints and five repetitions of three different hamstring exercises using three different loads.

Data Collection

Data will be collected from four muscles using a wireless surface electromyography (sEMG) system (Trigno Wireless EMG, Delsys, Boston, MA, USA; parallel bar configuration, inter-electrode distance 10mm, contact material 99.9% Ag, electrode size 37 x 26 x 15mm) from the participants' dominant limb. The dominant leg will be determined as the participant's kicking leg (Freckleton et al., 2013). The muscles analysed will be Gluteus Maximus, Biceps Femoris (long head), Semitendinosus and Medial Gastrocnemius. Skin preparation and electrode placement will be carried out in accordance with the recommendations of Hermens et al. (2000). All participants will be asked to shave their dominant limb prior to the day of testing in preparation for electrode placement. Prior to electrode placement the skin will be cleaned using an alcohol wipe. For Biceps Femoris (long head), the electrode will be placed on the midpoint of the line between the ischial tuberosity and lateral tibial condyle. For Semitendinosus, the electrode will be placed on the midpoint of the line between the ischial tuberosity and medial condyle of the tibia. For Gluteus Maximus, the electrode will be placed at the midpoint of the line between the sacral vertebrae and the greater trochanter of the femur. For the Medial Gastrocnemius, the electrode will be placed at 1/3 of the line between the fibula head and the heel.

To aid electrode placement, palpation of each muscle belly during light isometric contraction will be used and the quality of the sEMG signal will be visually checked (Higashihara et al., 2018). All electrodes will be placed over the muscle belly and longitudinally with respect to the muscle fibre with the location of each electrode outlined using a marker pen (Moore et al., 2014). While the measures proposed to maximise electrode attachment, the outline identified by the marker pen will serve to guide the reattachment of the electrode if they should fall off during testing. The electrodes will be attached to the skin with double-sided tape to the lower limb and a self-adhesive tape (Hypafix) will be placed over each electrode to secure them in place and to minimize movement artefacts from the lower limb during the running and exercise protocol (Albertus-Kajee et al., 2011). The quality of the sEMG signal will be visually checked once the electrodes have been secured in place.

Non-invasive reflective markers will be affixed to the tip of the acromion, greater trochanter of the femur, lateral femoral condyle of the femur, lateral malleolus of the fibula, lateral side of the calcaneus and the 5th metatarsophalangeal joint of the dominant arm and leg. Coordinate data will be recorded using a data motion analysis system (Vicon, 200Hz) (Vicon Nexus, Oxford Metrix Inc, UK). A Vicon Inertial Measurement Unit (IMU) will be placed on top of the foot in the laces of the participants running shoes and the data will be recorded using the data motion analysis system (Vicon, 1000Hz) (Vicon Nexus, Oxford Metrix Inc, UK). In order to place the electrodes and markers in the aforementioned locations, participants will be required to wear low cut socks, rugby shorts, which will be rolled up and taped to the minimum level required to expose the greater trochanter, and a training vest to expose the tip of the acromion.

Sprinting protocol

Each participant will be required to complete three x 40 m sprint running trials and this data will be used to normalise the sEMG data collected during the exercise protocol (Albertus-Kajee et al, 2011). All sprint trials will take place on an indoor synthetic running track (Mondo, Warwickshire, UK) in NIAC. Smartspeed timing gates (Smartspeed, Fusion Sport) will be used at 10 m intervals to provide 10 m split times as well as the total time to complete the sprint. The timing gates will also serve as markers for the sprint distance. The 30-40 m window of all sprint trials will be captured using two video cameras (100 Hz) to determine one stride of the gait cycle – which is defined as the point from ipsilateral foot contact to the following ipsilateral foot contact of the same foot (right foot to right foot contact) (Higashihara et al., 2018). The IMU will be used to record two consecutive touch down events and will be used to determine one stride of the gait cycle in conjunction with the video data. A five-minute rest period will be given between each sprinting trial (van den Tillaar et al., 2017). The video data will be stored securely on One Drive, and the footage will only be accessible to the research team. The video cameras will be positioned 5 m apart in the sagittal plane and 8 m away from the running plane.

Exercise protocol

The exercises that will be analysed include the prone hamstring curl, single leg bridge and single leg roman chair hold. All participants will complete one set of five repetitions of each exercise (Boyer et al., 2021) under three loading conditions determined as a percentage of the participants body weight. Due to the nature and demand of the exercises and the inherent differences between them the load will be determined as follows:

Single leg roman chair hold
10%, 20% and 30% body weight
Single leg bridge
5%, 15% and 25% body weight
P**rone hamstring curl**
20%, 35% and 50% body weight

In total, participants will perform 45 repetitions to complete the exercise protocol. A two-minute rest period will be provided between each set of five repetitions for each exercise and a five-minute rest will also be provided before repeating the exercises using the second and third loading condition. All exercises will be recorded using a video camera to synchronize the muscle activity with the different phases of each exercise and to capture the coordinate data from the motion analysis. The video data will be stored securely on One Drive and the footage will be restricted strictly to those on the research team. The data collection will take approximately 90 minutes per participant.

Data analysis The sEMG data will be analysed using Delsys EMGworks software (Delsys Inc., Boston, MA, USA) and Visual 3D software (Visual 3D v6, C-Motion Inc, Germantown, USA). The peak activity and integrated sEMG (iEMG) will be recorded for each exercise repetition and the mean values for each exercise and each loading condition will be normalised to the peak and iEMG recorded during the sprint that resulted in the highest peak activity and iEMG (Prince et al., 2021). Joint angles for the hip, knee and ankle will be computed from the coordinate data to quantify joint range of motion throughout the exercises. All statistical analysis will be carried out using the SPSS statistical analysis software. A two-way analysis of variance (ANOVA) with repeated measures will be used to analyse the data and if statistically significant interactions or main effects are found then Bonferroni's post hoc analysis will be used.	
A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
Click here to enter text.	
A6 Will the project have security sensitive implications?	No
A7 If yes, please explain what they are and the measures that are proposed to address them	
Click here to enter text.	

B PREVIOUS EXPERIENCE
B1 What previous experience of research involving human participants relevant to this project do you have?
I have completed three studies prior to this proposed study as part of my PhD thesis. These studies involved human participants and using the equipment and data analysis procedures which I require for this study. I also completed my MSc dissertation using human participants and electromyography. As a chartered physiotherapist my anatomical knowledge will aid the placement of electrodes and markers.
B2 **Student project only** What previous experience of research involving human participants relevant to this project does your supervisor have?
Dr Isabel Moore Dr Izzy Moore has experience conducting EMG and motion analysis studies. She has published in the field of lower limb mechanics for over 8 years, with a particular focus on injury and rehabilitation. **Professor Jon Oliver** Prof Jon Oliver has conducted extensive research in human performance, publishing over 120 peer-reviewed papers and supervising 16 PhD students to completion. This has included research examining injury, research examining sprinting and research using electromyography.

C POTENTIAL RISKS
C1 What potential risks do you foresee?
For the participants: **a) Musculoskeletal** The participants may experience fatigue as a result of completing the sprinting trials and also muscle soreness as a result of completing the hamstring exercises during data collection. There is also a potential risk of muscle strain injury, however the exercises being analysed are believed to help injury prevention. The data collection process presents no more risk than the participants experience during a routine training session.

b) sEMG and reflective markers
The sEMG electrodes will be attached directly to the skin with tape and therefore there is a chance that some of the participants may have a tape allergy. The data collection requires skin mounted markers to be directly located onto the participant and potentially attached with tape to the skin which may cause irritation.

c) Marker pen
Electrode placement will be outlined using a marker pen.

d) Power relationships
Due to the nature of the environment the participants will be recruited from, there may be issues with players feeling compelled to participate in the study to satisfy the wishes of their coach or club.

e) COVID-19
There is a risk of COVID-19 transmission between the participants and the research team which could influence the number of participants available to take part in the study and the timeline to complete data collection.

f) Data protection
Due to the nature of research, participant data will be collected and stored for processing

C2 How will you deal with the potential risks?

***Participants*:**
a) Musculoskeletal*

- All participants will complete a PAR-Q to ensure they can take part in the study.
- All participants will be familiarised to the training activities to be used during the intervention.
- Before any testing or training participants will undertake a standardised warm-up protocol.
- Rest periods will be provided in between each sprint trial, between the end of the sprint trials and start of the exercise protocol and between each set of exercises.
- Athletes will be instructed to wear appropriate clothing and footwear for testing.
- A health and safety check will be completed before each testing/training session to ensure there is minimal risk of trips, falls or other potentially injurious incidents.
- There will be one physiotherapist present during all data collection procedures and the NIAC staff have up to date first aid qualifications.
- Each participant will be advised to warm down after taking part in the data collection process.

b) sEMG and reflective markers*

- Ensure participants have no allergies to tape before attaching electrodes and markers.
- The electrodes and markers will be attached to the skin using a hypoallergenic tape to avoid any adverse skin reactions.

c) Marker pen*

- Ensure participants are informed and if they have any known allergy, marker pens are not to be used for marking skin.

*Appendix G details the risk assessment completed with regards to these elements of the data collection procedures.

d) Power relationships

- It will be explained explicitly to participants that they are under no obligation to participate and are free to withdraw at any time.
- The research team will meet with staff members in positions of authority and explain that the study is optional, and there should be no pressure on players to participate under any circumstances.

e) COVID-19

A COVID-19 specific risk assessment (RA) approved by the University following ethical approval will be adhered to and the RA procedures will apply to participants and everyone involved in data collection. Key points of the RA include:

- All participants will complete a COVID-19 symptom check questionnaire prior to arriving at the testing facility.
- Testing will take place in NIAC which is a well-ventilated indoor facility.
- All participants will be required to sanitise their hands prior to entering the testing area.
- Level 2 personal protective equipment (PPE; gloves, apron & visor) will be worn by the researcher during the placement of the sEMG electrodes.
- All participants will wear a face mask while the sEMG electrodes are being placed on their skin.
- The researcher and technicians supporting the data collection process will wear a face mask at all other times during testing.
- 2 m social distancing will be maintained at all other times during testing.
- Only one participant will be allowed to enter the testing area at any time.
- All equipment will be cleaned between trials with a surface sanitiser.

f) Data protection

- All consent forms will be uploaded to One Drive and will only be accessible by the research team.
- All data will be collected on secure private computers and stored remotely on OneDrive, which will only be accessible by members of the research team.
- Participants will be assigned an ID code at the start of the study, and all collected data will be collected under this anonymised ID code.
- The names and related ID codes of participants will be inputted into an excel document which will be password protected. This password will only be shared with the research team, and the document will be stored on secure private computers.
- The participants will be identifiable on the video data and the videos will be stored securely on OneDrive. Participants will be made aware that the data cannot be properly anonymised due to the videos but they will be reassured that the data will be stored securely.
- All personal data will be processed in line with Article 6(1)(a) and Article 9(2)(a) of the General Data Protection Regulation, 2018.

When submitting your application, you **MUST** attach a copy of the following:

- All information sheets
- Consent/assent form(s)
- Withdrawal of consent form

An exemplar information sheet, exemplar participant consent form and exemplar participant withdrawal form are available via the research section of the Cardiff Met website (see section on Ethics Governance). These are based on good practice and will be useful in the majority of cases. However, it is recognised that in some cases a project will be subject to requirements from an external body. Use of these exemplars is therefore not obligatory.

APPENDIX 7 – PARTICIPANT INFORMATION SHEET (STUDY 4)

PARTICIPANT INFORMATION SHEET

Title of research project: The effect of load on hamstring muscle activity and lower limb kinematics during hamstring training exercises

CMU approval number: PGR-4253

We would like to invite you to take part in the above-named research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please therefore take time to read the following information carefully.

What is the purpose of the study?

Hamstring strain injuries (HSI) are the most common muscle injury in sport with high-speed running being the most common activity at time of injury. HSI accounts for between six and 29% of all injuries reported in Australian rules football, rugby union, soccer, cricket and track sprinting. Hamstring function is crucial to sprint performance meaning hamstring injury has significant consequences on an athlete's performance. The re-injury rate for HSI has been reported as being as high as 31%. The risk of re-injury is reported to be most significant within the first two weeks of return to sport and reoccurrences are often more severe than the initial injury. This has great consequences in terms of finance and the time that the athlete loses from both training and competition.

With HSI injury and re-injury being such a common occurrence in sport it suggests that current prevention and rehabilitation programmes which target this injury have not been successful, therefore the challenge of managing HSI remains. The precise mechanism and timing of hamstring strain in sprinting is unknown however the late swing and early stance phases of high-speed running are when HSI most commonly occur. Therefore, the aim of this study to analyse hamstring muscle activation during different hamstring exercises which generate muscle activity that is similar to that which occurs during the injury risk phases of high-speed running. The findings of the study will help to inform HSI prevention and training programmes.

Study duration:

The total duration of the study will be 12 weeks, however data collection for each participant will only take approximately 90 minutes after which time you will not need to return for any further testing.

Why have you been asked?

In order to participate you must meet the following criteria:

- Currently playing in the University 1st rugby team
- Aged between 18-25 years old
- Taking part in regular training (minimum of 45 minutes x 3 times per week)
- Have no history of lower limb injury in the last 12 months

- Have no history of lower limb surgery
- Meet the requirements of the COVID-19 questionnaire
- Meet the requirements of a PAR-Q questionnaire

Do I have to take part?

Participation in the study is entirely voluntary and you will be asked to complete and sign a participant consent form prior to any involvement. There is no risk to your selection or standing within the rugby team based on your decision to take part. The principal researcher will remain vigilant to any staff member attempting to influence your decision. If at any point you no longer wish to participate in the study, you are completely free to do so. A participant withdrawal form will be sent to you alongside the participant consent form and includes more details of what actions will be taken following your request to withdraw.

What does your participation involve?

Prior to agreeing to take part in the study you will be asked to read the information sheet and will be given the opportunity to ask any questions. The experimental protocol will then be explained to you to ensure that you understand the procedure prior to signing a consent form to confirm that you are happy to take part. You will need to attend the National Indoor Athletics Centre (NIAC) at the School of Sport and Health Sciences, in Cardiff Metropolitan University for one familiarisation and one testing session – the familiarisation session will take place a week before testing.

On the day of testing the research will measure your height and body weight and will then ask you to complete a standardised 15-minute warm-up. After the warm-up reflective markers will be placed on your shoulder, hip, knee, ankle and foot and electrodes will be placed on your right thigh, buttock and calf and reflective markers will be placed on your hip, knee and ankle. Once the electrodes and reflective markers are in place you will be asked to complete three x 40 m sprint running trials and five repetitions of three different hamstring exercises under three different loading conditions (the total number of repetitions to be completed is 45). Between each sprint trial you will be given a four-minute rest period and then a 10 minute-rest after completing the final sprint and prior to starting the exercise protocol. A two-minute rest will be provided between each set of five repetitions for each exercise and you will have a five-minute rest period between the three loading conditions being analysed. All sprint trials and exercises will be video recorded to allow the researcher to complete the necessary data analysis of your muscle activation.

Are there any risks to your participation?

There are very few risks associated with this study. You may experience fatigue and/or muscle soreness as a result of completing the hamstring exercises and there is also a potential risk of muscle strain injury. However, sprinting and exercise protocol presents no more risk than you experience during a routine training session. The exercises will be prescribed to you under the guidance of a qualified Physiotherapist and you will be required to complete a warm-up prior to completing the protocol and will be under constant supervision by one or more of the research team. The data collection process involves the placement of electrodes and reflective markers on the skin which may cause some skin irritation, however hypoallergenic tape will be used to attach the electrodes and markers to avoid any adverse skin reactions.

There is a risk of COVID-19 transmission during the testing. To minimise this risk, you will be required to complete a COVID-19 symptom checker and upon entry to NIAC you will be asked to wear a face mask and sanitise your hands prior to testing. During the placement of electrodes and reflective markers the research will wear level 2 PPE while you continue to wear your face mask. During the remainder of the testing procedure social distancing can be maintained and therefore you will not need to wear a mask during this time. There is no risk to your selection or standing within the rugby team based on your decision to take part in the study. The principal researcher will remain vigilant to any staff member attempting to influence your decision to take part.

Are there any benefits?

There will be no individual benefit from taking part in this study. It is hoped however that the results of the study will inform the management of HSI and will contribute to the development of hamstring training and injury prevention programmes by using the most appropriate hamstring exercises.

What happens to the results once the study is finished?

Once you have completed your participation in the study, the data will be collected by the research team and analysed as part of a PhD research project. The subsequent report may be submitted for publication in an academic journal and the video data and findings may be used in conference and teaching presentations. You will not be identifiable on the video data as your face will be blurred to ensure anonymity.

How will my data and my privacy be protected?

All data will be stored remotely on a secure OneDrive, which will only be accessible by the research team. Only data that is required for the completion of the study will be collected and will be deleted after 10 years. All participant names will be replaced with individually assigned numeric ID codes. Only the research team will have access to the decryption key identifying participants by their codes, and this will be deleted once the anonymisation process is complete. Full anonymity will be maintained as the video data will be blurred such that your face is not identifiable and the video data will be stored securely and only the research team will have access to this data.

Who is involved in the project?

Principal Researcher: Adeline Miles (The School of Sport and Health Sciences, Cardiff Metropolitan University)

Supervisors: Dr Isabel Moore and Professor Jon Oliver (The School of Sport and Health Sciences, Cardiff Metropolitan University)

This project has been approved by the Cardiff Metropolitan University Research and Ethics Committee.

If you have any questions regarding any of the information presented on this form please email Adeline Miles (ajmiles@cardiffmet.ac.uk) for further information, alternatively, you can contact Cardiff School of Sport & Health Sciences (029 2041 6771) or the Sport Ethics team (sportethics@cardiffmet.ac.uk) to raise any concerns you have with the project.

Thank you for taking the time to read this information sheet.

APPENDIX 8 – PARTICIPANT CONSENT FORM (STUDY 4)

PARTICIPANT CONSENT FORM

Reference Number: PGR-4253

Participant name or Study ID Number:

Title of Project: The effect of load on hamstring muscle activity and lower limb kinematics during hamstring training exercises

Name of Principal Investigator: Adeline Miles

Research team: Dr Isabel Moore and Professor Jon Oliver

Name of person taking consent: Adeline Miles

Participant to complete this section (please initial each box):

1. I confirm that I have read and understood the information sheet for this study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time during the data collection period, without giving any reason.	
3. I understand that once data collection has been completed, I may request withdrawal of my data from the study at any time prior to completion of data analysis without giving any reason for up to 3 months after my visit to NIAC for testing.	
4. I understand that once data analysis has been completed, I have the right to be forgotten and can request erasure of personal data recorded during this project. I further understand that beyond the completion of data analysis it will be necessary for the university to retain non-personal data for verification purposes for 10 years.	
5. I agree to take part in the above study.	
6. I agree to the testing session being video recorded and for the recorded data to be used for analysis.	
7. I am aware that the recorded data will not be identifiable, and I agree for this data to be used in subsequent presentations / conferences and journal publications.	

Signature of participant:	Date:
Signature of person taking consent:	Date:

Any information you provide will be treated in accordance with data protection principles for the purposes specified within the Participant Information Sheet. Cardiff Metropolitan University will process your personal data in line with Article 6(1)(a) and Article 9(2)(a) of the General Data Protection Regulation 2018 which specifies that your personal data can only be processed with your explicit consent. By placing your initial in the boxes above and signing the form you are confirming that you have understood the reasons for obtaining your data and you are happy to take part in the study. Please note that you have the right to withdraw consent at any point. Should you wish to invoke that right please contact Adeline Miles (ajmiles@caridiffmet.ac.uk). A Participant Withdrawal Form is available from the Cardiff Met website

APPENDIX 9 – PARTICPANT WITHDRAWAL FORM (STUDY 4)

PARTICIPANT WITHDRAWAL FORM

Explanatory Notes for Research Study Participants:

Participation in a research study is voluntary and is based on a full understanding of what that participation will involve. Individuals who have consented to take part in a research study at Cardiff Metropolitan University are fully entitled to withdraw their consent at any point, without prejudice. However, it should be noted that the timing of a request to withdraw from the project will have a bearing on the type of action the University is reasonably able to take to honour the request.

If you decide that you no longer wish to participate in the project whilst the researcher is in the process of collecting data, you can expect for any data collected from you to be withdrawn (3 months after data collection) and not used in the data analysis phase or any publication of the outcomes of the project.

If you decide that you no longer wish to participate once the researcher has begun analysing the data, or when the data analysis has been completed it becomes much more difficult to remove your data from the overall data set. However, you can expect every effort to be made to remove your data from the project and, as a minimum, any data from which you can be identified will be removed from the project. The principal investigator on the project will discuss with you which data will be removed and the reasons why any remaining data cannot be withdrawn from the project. If you would like to exercise your right to be forgotten once the project has completed, all of your personal data from which you can be identified will be deleted from records held by the university in relation to the project.

If you would like to withdraw as a participant in a research project, please complete the form overleaf and return to the Principal Investigator.

Reference Number: PGR-4253

Participant name or Study ID Number:

Title of Project: The effect of load on hamstring muscle activity and lower limb kinematics during hamstring training exercises

Name of Principal Investigator: Adeline Miles

Name of the person to whom this form should be submitted: Adeline Miles

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Participant to complete this section. Please initial one of the following boxes:

1.	I confirm that I wish to withdraw from the study before data collection has been completed and that none of my data will be included in the study.	
2.	I confirm that I wish to withdraw all of my data from the study before data analysis has been completed (3 months after data collection) and that none of my data will be included in the study.	
3.	I confirm that although the results of the study have already been produced and cannot change, I wish to be forgotten and that all of my personal data is deleted from verification records maintained by the university about the study. I understand that this means that only those data identifying me will be deleted.	

Your name is required to verify that you have withdrawn your data from the study as specified above. In the case of (3), above, we will need to retain this form until 1st September 2031 at the maximum.

It may be necessary to share this information with internal examiners, external examiners, and / or journal editors for the purposes of verification of findings and tracing results of studies to the raw data used.

This form will be stored securely until 1st September 2031 at the maximum, when it will be destroyed, and will not be shared with anyone else.

Signature of participant:	Date:
Signature of person who will ensure that the stated data have been deleted:	Date:

APPENDIX 10 – PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q) (STUDY 4)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____ DATE ____________________

SIGNATURE OF PARENT ____
or GUARDIAN (for participants under the age of majority) WITNESS ____________________

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

Supported by: Health Canada Santé Canada

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