AN EXPLORATION INTO THE ASSESSMENT OF HIP EXTENSION STRENGTH AND ITS IMPORTANCE FOR PERFORMANCE IN PROFESSIONAL SOCCER.

THOMAS JAMES STAFFORD KING

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Abstract

Hip extension is a joint action that contributes to athletic movement during performance in various sports. Within the sport of professional soccer, high intensity efforts encompass an important proportion of athletic movement and optimal hip extensor functioning can be seen as a crucial action for the successful performance of such actions. Perhaps related to the importance placed upon high intensity efforts in soccer, the number of hamstring strain injuries that occur are of major concern to practitioners within the field. As such, great efforts are made to establish methods of managing and mitigating these injuries, one of which being improving hip extension function. Methods of establishing an individual's maximal hip extension strength capacity are available yet are not void of several clinical and practical limitations. As such, understanding the relationship between the specific ability of hip extension with performance and injury related measures are difficult to investigate. Therefore, it may be of use to investigate the development of new strength assessment methods.

In study 1 (chapter 3) a framework of considerations was outlined that surround various methodological and theoretical concepts believed to influence the subsequent validity, reliability and operational success of hip extension assessment tools in the applied field. These considerations arose from information in previous scientific research and from the research team's (PhD candidate and supervisors) wealth of experience working in applied professional sport. Throughout the framework of considerations, the assessment tools currently available for hip extension strength were critiqued and a rationale for the development of a new tool was outlined. Further into the chapter the adherence of these considerations was presented throughout the development of a new assessment tool (Hip Extension Bench). Finally, the ultimate section of this chapter then introduced information surrounding practical application of the Hip Extension Bench.

In study 2 (chapter 4) the sensitivity of the Hip Extension Bench was investigated where the research team assessed muscle activity and force changes in response to various hip flexion positions. The investigations were undertaken with a mixed population of elite soccer players (n = 10), competitive sprinters (n = 10) and recreationally active males (n = 5) and consisted of assessment across 6 different hip positions (70, 60, 45, 30, 15 and 0° hip flexion). Results displayed precise and specific changes in individual hip extensor

muscle activity and force production under maximal isometric contractions at different hip joint angles. Gluteus maximus muscle peak activity was pronounced at positions of inner range hip flexion (0 and 15°) whereas maximum force and biceps femoris long head and semitendinosus peak activity was pronounced at positions of greater hip flexion (60 and 70°). These data suggest that the Hip Extension Bench can be manipulated to selectively target specific hip extensor muscles and careful precisions must be adhered to upon assessment setup to confirm standardised conditions.

In study 3 (chapter 5) the test-retest reliability of the Hip Extension Bench under non-fatigued conditions was investigated. A group of 40 elite youth soccer players and 15 competitive sprinters undertook maximal isometric hip extension contractions at two angles (15 and 60°) on two occasions with a minimum and maximum of 7 and 14 days between test days. Generally, both cohorts demonstrated good reliability of bilateral and unilateral isometric hip extension strength assessments. The findings also demonstrated the difficulties surrounding data collection in the applied field where several complications may arise that influence the subsequent findings and informed decisions that are made on reflection of the data.

In study 4 (chapter 6) the first implementation of the Hip Extension Bench within research surrounding isometric hip extension strength and sprint-acceleration and jump performance associations was presented. A sample of 10 competitive sprinters completed a minimum of three 40 m sprints on test day 1 and a comprehensive battery of strength and power assessments on test day 2 with a minimum and maximum of 7 and 14 days between each test day. The main findings confirmed that isometric hip extension strength was highly correlated with several force-based variables of sprint-acceleration performance (theoretical maximum force; F_0, total force; $F_{\mathrm{T\ Peak}}$, total force across distances of 2, 20 and 40 m; $F_{\mathrm{T\ 2,\ 20\ \&\ 40\ m}}$, mean horizontal force; $F_{\mathrm{H\ Mean}}$, horizontal force across distances of 2 and 20 m; $F_{\mathrm{H\ 2\ \&\ 20\ m}}$ and peak power; P_{max}) and jump performance in the horizontal direction (the sum of left and right leg horizontal countermovement jumps; UL HCMJ Sum). These findings provide evidence for the role and importance of hip extension strength, specifically under isometric conditions, in high intensity effort performance.

Overall, these findings suggest that a new assessment tool for isometric hip extension strength has been developed that is suitable for application in the environment of applied professional sport. The findings also confirmed the important of hip extension for high intensity effort performance and in conclusion provide a strong rationale for the implementation of the Hip Extension Bench for future research and application in performance and injury management.

Declaration

I declare that the work presented in this thesis, which I submit for assessment on the programme of study leading to the award of PhD, is entirely my own. The Hip Extension Bench assessment tool developed in this thesis was achieved with the help of the Faculty of Engineering and Technology at Liverpool John Moores University and was largely funded by Liverpool Football Club. All efforts have been made to ensure that the work is original and does not (to the best of my knowledge) breach any copyright laws and has not been taken from the work of others.

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List of abbreviations

Add_{mag}; adductor magnus
BF_{lh}; biceps femoris long head
CKC; closed kinetic chain
COD; change of direction
COM; centre of mass
EMG; electromyography
F_0; theoretical maximum force
$F_{\text{H 40-2 m}}$; horizontal force across distances of 2, 5, 10, 15, 20, 25, 30, 35 and 40 m
F_{Hpeak}; peak horizontal force
F_{Opt}; optimum force for peak power
$F_{\text{T 40-2 m}}$; total force across distances of 2, 5, 10, 15, 20, 25, 30, 35 and 40 m
F_{T}; total force
GCT; ground contact time
G_{max}; gluteus maximus
HCMJ_{sum} / HCMJ_{L} / HCMJ_{R}; horizontal countermovement jump sum / left / right
HEB; Hip Extension Bench
$\text{HEB}_{\text{70, 60, 45, 30, 15 \& 0}}$; HEB assessment at hip flexion angles of 70, 60, 45, 30, 15 and 0°
HIE; high intensity efforts
HSI; hamstring strain injury
MD; minimal difference
OKC; open kinetic chain
P_{H}; horizontal power
P_{max}; peak power
r; correlation coefficient
r^2; coefficient of determination
$RF_{\text{40-2 m}}$; ratio of force across distances of 2, 5, 10, 15, 20, 25, 30, 35 and 40 m
RF_{peak}; peak ratio of force
sEMG; surface electromyography
SM; semimembranosus
SOC; group of soccer players
SPR; group of sprinters
ST; semitendinosus

UL; unilateral

V_0; theoretical maximum velocity

VCMJ / VCMJ_L / VCMJ_R; vertical countermovement jump / left / right

V_{max}; maximum velocity

V_{Opt}; optimum velocity for peak power

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Chapter 1

General introduction

1.1. Introduction

Soccer is a multifactorial sport and the modern professional game is now underpinned by a multidisciplinary team that must work cohesively in order to achieve success. For sports science and medical departments, two fundamental constructs that are paid great focus are the development of athletes' physical ability and the management of injury susceptibility. This is most probably due to the convincing and direct impact both of these constructs are believed to have on the success of organisations in the sport. In respect to this thesis, the term performance seeks to govern the areas of physical assessment, athletic development and injury susceptibility of athletes. Within this, the daily workload of a sports scientist / strength and conditioning coach in professional soccer extends to monitoring of training load, implementation of injury prevention programmes and programming of individualised athletic development sessions. As such, the performance of said practitioners work is often judged on specific improvements to an athlete's strength, speed or power capacity and the number of injuries that the team endures.

In order to improve physical performance and reduce injury risk, there are a number of factors that must be considered. For example, the multifactorial nature of soccer requires athletes to be strong, fast, explosive and have excellent aerobic and anaerobic capacity in order to perform for the full duration of a match. In addition, the requirement to frequently sprint, jump and change direction within a contact environment that is reactive in nature means that various injury mechanisms are possible. Therefore, ideally extensive periods of time would be devoted to the development of all areas of an individual's profile. However, modern soccer is now governed by the presence of heavy fixture schedules inclusive of domestic league and tournament competitions and even periods of international fixtures. In addition, the commercialisation of the game now demands an increased amount of time to be devoted to travelling to and from fixtures across the world and attendance of various media and social appearances. As such, the remaining time is largely devoted to focused soccer specific training sessions and periods of recovery in order to optimise technical and tactical competence and athlete readiness to perform.

Because of the time-constrained environment that exists in soccer and the requirement of teams to compete up to three times per week, sports science departments are required to be clever with prioritisation of assessment opportunities and training interventions. As such, practitioners seek to individualise programmes for their athletes so that the limited time available can be spent effectively by improving facets that require the greatest attention. In order to do so, it is necessary that means of measuring the various aspects of an athletic profile are available. Such measures may include joint by joint mobility and flexibility screening, aerobic capacity protocols, sprint-acceleration testing and the collection of various strength and power diagnostics.

At the surface level, it is important to consider the needs analysis of the sport when deciding upon utilising assessment methods, where high intensity efforts (HIE) are largely present and are believed to exist during the most influential situations in a match. From an injury surveillance perspective, common injuries such as hamstring strain injuries (HSI) and severe injuries such as those to the knee ligaments are also important considerations. Both of these points may be used to inform initial decisions for the global screening of full squads. The next steps would be to individualise screening methods where necessary. Perhaps due to the frequential occurrence of injury to the hamstrings and the importance of HIE performance in soccer, the assessment of posterior chain strength is common. The hamstrings in particular have been isolated in order to investigate their specific contribution to injury management and performance enhancement, yet the addition of the gluteus maximus (G_{max}) to assessment batteries is seemingly absent. This comes as a surprise, especially considering the muscle is considered to be the "powerhouse" of force production in the lower limbs throughout global athletic performance. Until now, the synergistic functioning of the hamstrings, gluteus maximus and adductor magnus deemed hip extension, has been confirmed to have a central role in force production during athletic movement and specifically HIE performance. For these reasons, training methods to isolate this joint action are commonplace within programming structures across various sports. In addition, a recent emergence of optimal hip extension function for HSI management has provided suggestions that directed training methods may provide dual benefits for performance enhancement and injury management purposes.

Unfortunately, there is an absence of hip extension assessment methods in the applied field which provides some difficulty in determining the specific needs analysis of the athlete in respect to this action. As such, it seems to be reasonable to hypothesise that the inclusion a new strength assessment tool would provide useful information for further indication of an athlete’s athletic profile. However, for a new tool to be deemed suitable, rigorous reliability and validity checks must be undertaken. These investigations confirm the extent to which data is representative of the action it is supposed to reflect and the respective error that expected to be seen when collecting information. Therefore, it seems that there is potential for the development and implementation of a new strength assessment tool, but only after a period of comprehensive research to confirm its suitability.

The aims of the project are,

1.2. Aims and objectives of the thesis

The aim of this project is,

Aim 1. To investigate maximal hip extension strength in professional soccer with respect to assessment and physical performance

The following objectives have been constructed to successfully achieve the aim,

Objective 1. To determine the specific role of hip extension in professional soccer and critique the current tools available to assess hip extension strength, with a view of rationalising the development of a novel tool.

Objective 2. To develop a novel tool to assess isometric hip extension strength (hip extension bench, HEB) that successfully meets a framework of considerations required for the development of such tools.

Objective 3. To investigate the sensitivity of the HEB assessment tool to detect change in muscle activity and force production in response to changes in hip flexion angle.

Objective 4. To investigate the test-retest reliability of the HEB assessment tool across two different bilateral and unilateral hip flexion angles.

Objective 5. To investigate the association between isometric hip extension strength measured with the Hip Extension Bench strength assessment tool and sprint-acceleration and jump performance.

Relating to the above objectives, the hypotheses of the project are,

Hypothesis 1. It was hypothesised that current measures of hip extension strength will not sufficiently meet the framework of considerations required to pass as a suitable assessment tool.

Hypothesis 2. As a consequence of successfully adhering to the developed framework of considerations, it was also hypothesised that a successful novel assessment tool will be developed. The ‘success’ of this tool will be measured by the effective completion of objectives 3 and 4.

Hypothesis 3. It was hypothesised that the strength capacity of the hip extensors when measured with the HEB assessment tool would hold a positive relationship with sprint-acceleration and jump performance in the forwards direction.

Chapter 2

Literature Review

2.1. Introduction

2.1.1. Physical demands of soccer

Physical performance in soccer is governed by both anaerobic and aerobic energy systems which are required to function simultaneously over the duration of competition (Bangsbo, 1994a; 1994b; Bangsbo *et al.,* 2006; Stølen *et al.,* 2005). The intermittent nature of the sport involves bouts of high intensity efforts (HIE) interspersed between the predominantly aerobic nature of the sport. These HIE can be broken down into sprint-acceleration, jump and change of direction (COD) tasks and in some cases also embody actions such as ball striking, tackling and wrestling for the ball. As the duration of competition lasts for a minimum of 90 minutes, it is important for athletes to be able to consistently reproduce these efforts throughout the full course of a competitive fixture. As such, the extent to which a team can repeat HIE successfully has been viewed as a causal indicator for successful performance (Impellizeri & Marcora, 2009). The physiological underpinning of HIE is generally accepted to be governed by a combination of maximal force production and rapid velocity of contraction (Suchomel *et al.,* 2016) in order to accelerate the body's centre of mass quickly in the direction of interest. Consequently, it may be viewed that development of maximal strength, speed, power, agility and endurance are all said to be crucial attributes to ensure optimal preparation for competition during training.

2.1.2. High-intensity performance in modern soccer

The evolution of soccer means that the physical and technical demands are ever increasing, and the physical requirement of athletes must complement this if success is expected (Barnes *et al.,* 2014; Bradley *et al.,* 2016; Konefał *et al.,* 2019). In the modern game, the ability to reproduce HIE's is ever-increasing (Barnes *et al.,* 2014; Bush *et al.,* 2015; Faude *et al.,* 2012). Running faster, change direction quicker and jumping higher are now consistently believed to heavily determine success during individual duals on the pitch and over the course of competition. As such, developing the several attributes that underpin these actions such as strength, speed and coordination is crucial. However, an inability to cope with the increase in physical demands may be detrimental to the wellbeing of athletes. Therefore, it is a primary responsibility of the sports science and medicine departments to ensure that their athletes are sufficiently equipped to manage these increases in competitive demands and excel when in competition.

2.2. Injury in soccer

2.2.1. Hamstring strain injury prevalence

Hamstring strain injuries (HSI) have progressively increased in soccer, a level which now leaves them as the most common soft-tissue injury in the sport (Ekstrand *et al.*, 2016; Jones *et al.*, 2019). Referring to the previous section, one explanation for this may surround the inability of athletes to sustain the greater physical demands that are now required of them during a match. This may also be emphasised for teams with a greater training or competitive fixture schedule and those without a "winter break" (Ekstrand *et al.*, 2018). During these circumstances, the accumulation of physiological and psychological stress may rise to levels that exceed an athlete's capacity. Throughout a competitive match this cumulative increase in stress may develop towards the end of each half and provide some explanation as to why athletes are most susceptible to injury during these periods in play (Woods *et al.*, 2004; Ekstrand *et al.*, 2011; Cloke *et al.*, 2012). Furthermore, although evidence surrounding HSI mechanisms and prevention methods has increased (as will be discussed below), the implementation and compliance rates of such knowledge and methods in practice may not be sufficient (Cuthbert *et al.*, 2019). Finally, information in the following sections surrounding hip extension as opposed to knee flexion for HSI management may provide further explanation for this.

2.2.2. Injury burden and team success

Time away from the sport due to injury can be costly to success where reduced athlete availability has been associated with lower league ranking, fewer games won and goals scored and less total points in soccer (Eirale, 2012; Hägglund *et al.*, 2013; Drew *et al.*, 2017). Athletes in top level soccer are now seen to generally spend anywhere between 8 and 28 days away from team training (Hallén & Ekstrand, 2014; Ekstrand *et al.*, 2019) and reinjury rates can sit anywhere between 14 and 63 % in team sports (Wangensteen *et al.*, 2016; de Visser *et al.*, 2012; Ekstrand *et al.*, 2011) and generally towards the lower end of the range in soccer (Hallén & Ekstrand, 2014; Ekstrand *et al.*, 2011).

Consequently, sports science and medicine departments spend significant amounts of effort attempting to understand the most suitable and effective methods of managing HSI risk in their specific teams.

2.2.3. Epidemiology of hamstring strain injury

Injury mechanisms. In order to understand how to manage and prevent HSI, an understanding of the mechanisms for injury is crucial. Hamstrings are biarticular muscles that act as knee flexors and hip extensors. Generally, HSI occurs during sprint- or stretch-induced type activities Liu *et al.* (2012) where the muscle in debt fails to meet the force requirements necessary to reverse the limbs knee extension and hip flexion. The specific time for sprint-induced injury to occur is at the late-swing phase (Chumanov *et al.,* 2012; Schache *et al.,* 2012; Liu 2017) where hip flexion and knee extension occurs exposing the hamstrings to a stretch at proximal and distal ends (Kuitunen *et al.,* 2002). At this stage, the hamstrings are exposed to great forces (Yu *et al.,* 2008; Zhong *et al.,* 2017), especially as running velocity increases (Chumanov *et al.,* 2007). Unfortunately, the direct mechanism for sprint-induced HSI is unknown and the precise behaviour of muscle fibres during these times is unclear (Van Hooren & Bosch, 2017; Thelen *et al.,* 2005; Chumanov *et al.,* 2007). Van Hooren & Bosch (2017) would contend that the hamstrings undergo quasi-isometric actions during late swing. Alternatively, Thelen et al. (2005) and Chumanov et al. (2007) would dispute this with musculoskeletal modelling of human sprint running claiming “negative work” via eccentric lengthening of the hamstring muscles. The literature presented in the research from Van Hooren & Bosch (2017) is generally based on animal studies with the use of bullfrogs (Azizi et al., 2014) and quadruped running animals such as dogs (Gregersen *et al.,* 1998), rats (Gillis *et al.,* 2001; 2002) and goats (Gillis *et al.,* 2005). Based upon the simple fact that frogs jump and that the other animals are quadrupeds, the running gait exhibited is different to that of bipedal animals (humans). Furthermore, humans do not necessarily have the same ratio of muscle to tendon size as other animals (Paul, 2001). Therefore, the assumption that the muscle-tendon tissue behaves in the same way during motion is perhaps unlikely. As such, to date the exact behaviour of the hamstrings during late-swing in human sprinting is not confirmed. The mechanisms around stretch-induced HSI are slightly clearer (Askling *et al.,* 2007), however considering sprint- and stretch-induced injury mechanisms to be similar seems to be inappropriate (Ruan, 2018). This uncertainty may provide some reasoning for the management issues of sprint induced HSI in sports such as soccer.

Risk factors. After understanding the general mechanisms for injury, it is important to determine the individual factors that may increase or decrease the risk of injury occurrence.

External activity profile related risk factors. Overloading an action will lead to fatigue and doing so to an extent that is far greater than what the body can withstand may lead to injury. For instance, multiple repeated sprint efforts have been found to reduce subsequent eccentric torque and neural activity of the biceps femoris long head (BF_{lh}) muscle (Timmins *et al.,* 2014). In addition, repeated sprint performance decrements are greater in those with previous HSI (Røksund *et al.,* 2017; Lord *et al.,* 2018). Exposing athletes to rapid increases in high-speed and sprint running distances above their habitual load has been found to increase the chances of HSI in Australian rules football, Gaelic football and soccer (Duhig *et al.,* 2016; Bowen *et al.,* 2016; Windt *et al.,* 2017; Malone *et al.,* 2017). Having said this, when chronic load is too low and too few maximum speed exposures are given, injury risk is again increased (Colby *et al.,* 2018). Similar findings have also been evidenced in elite soccer for acceleration related variables of load management (Bowen *et al.,* 2019) and these instances can be deemed under preparedness. Therefore, it has been suggested that athletes need to be exposed to sufficient amounts of sprint-acceleration running volume and intensities in order to prevent initial and recurrent HSI.

Internal musculoskeletal related risk factors. It is evident that individualisation and management of external training load is key. However, several physiological and biomechanical variables may influence the frequency and intensity to which an athlete is able to cope with the external load demands (Malone *et al.,* 2019). Comprehensively researched modifiable factors related to HSI include eccentric knee flexor strength (Fousekis *et al.,* 2011; Opar *et al.,* 2015; Timmins *et al.,* 2015; Cuthbert *et al.,* 2019), muscle fascicle length (Timmins *et al.,* 2015; 2017; Cuthbert *et al.,* 2019) and interlimb asymmetry (Fousekis *et al.,* 2011; Zakas *et al.,* 2006; Shield & Bourne, 2018; Al Attar *et al.,* 2016), whereas non-modifiable factors include age (Hägglund *et al.,* 2006; Henderson *et al.,* 2009; Gabbe *et al.,* 2006; Engebretsen *et al.,* 2010) and previous HSI (Engebretsen *et al.,* 2010; Gabbe *et al.,* 2006; Tokutake *et al.,* 2018). Over the years research practitioners have attempted to isolate specific capacities that may relate to injury susceptibility and provide recommendations on specific thresholds or strategies to ensure their athletes are “safe” from injury. Having said this, it may be suggested that some risk factors outweigh others in the order of importance. For instance, the injury risks associated for a particularly weak athlete with no interlimb hamstring strength asymmetry is probably different to that of a very strong athlete with an interlimb hamstring strength asymmetry of 11%. Therefore, practitioners must be concise when determining which risk factors to place greatest importance on.

Prevention methods. Sport-specific recommendations and interventions have then been made with a goal of increasing fascicle length (Petersen *et al.,* 2011; van der Horst *et al.,* 2015), eccentric knee-flexor strength (Timmins *et al.,* 2016) and minimising interlimb asymmetry (Buckthorpe *et al.,* 2019). Although individual risk factors exist, a holistic view of HSI prevention is encouraged where a combination of confounding factors will be responsible for increasing or decreasing an athlete’s susceptibility to injury (Foreman *et al.,* 2006; Mendiguchia *et al.,* 2012).

Although the awareness of risk factors for HSI has increased, injury rates aren’t dropping (Ekstrand *et al.,* 2016). Various reasons may be presented for the reasons why this may be the case, one of which surrounding the compliance and acceptance of research methods in the applied field (Goode *et al.,* 2015; Bahr *et al.,* 2015). In addition, emerging evidence surrounding a focus of proximal hamstring focus and hip extension has developed in recent years with favourable initial findings. Therefore, the remainder of this section aims to examine this new avenue to HSI management.

2.2.4. Hip extension and hamstring strain injury

Ideas surrounding hip extension for managing HSI will be divided into three sections. Firstly, the “direct” impact that targeted hip extension exercise may have on hamstring, and primarily BF_{lh} development will be presented. Following this, the “indirect” and synergistic influence that other hip extensors (gluteus maximus; G_{max} and adductor magnus; Add_{mag}) may have on HSI management is considered. Finally, the role that hip extension may play in managing trunk control as a risk factor for HSI is outlined.

2.2.4.a. Targeted hip extension training

By understanding the specific site of an injury, inferences can be made into the reasoning of such injuries and a rationale can be made for targeting specific work in the rehabilitation process. The most commonly injured hamstring muscle and site of injury during sprint-induced strains is the BF$_{lh}$ typically towards the proximal end (Ekstrand *et al.,* 2012; De Smet *et al.,* 2000). The BF$_{lh}$ muscle has a greater moment arm at the hip than it does at the knee (Chleboun *et al.,* 2001; Visser *et al.,* 1990), causing the muscle to undergo greater lengthening in response to sagittal hip joint motions (Visser *et al.,* 1990). This means that the hamstrings muscles may undergo a nonuniform change in recruitment upon hip or knee biased exercise and that traditional methods of knee-dominant hamstring training for injury prevention should be challenged (Tyler *et al.,* 2017; Guex *et al.,* 2013). Traditional hamstring exercise is characterised by training at shorter muscle lengths and selective recruitment of the medial hamstrings (semitendinosus; ST and semimembranosus) such as prone leg curls and the Nordic hamstring exercise (Bourne *et al.,* 2017b; Hegyi *et al.,* 2019).

Training at different muscle lengths may also have important implications for the manipulation of fascicle length properties over time. Fascicle length increases are generally believed to be achieved through eccentric exercise (Gérard *et al.,* 2020; Franchi *et al.,* 2017), yet some literature involving concentric exercise exists providing similar improvements (Blazevich *et al.,* 2007). For this reason, Guex *et al.* (2013) proposed for long muscle length training to be another important stimulus for increasing fascicle length. However, commonly utilised hamstring exercise modalities at relatively short muscle lengths, such as the Nordic hamstring exercise, generally provide large success when it comes to increasing fascicle length (Gérard *et al.*, 2020; Cuthbert *et al.*, 2020). Consideration of further factors within exercise selection have been made, such as the magnitude of load applied to the muscle or level of muscle excitation that a muscle exhibits in response to this load (Bourne *et al.,* 2016; Tsaklis *et al.,* 2015; Mendiguchia *et al.,* 2013; Mendez-Villanueva *et al.,* 2016; Schoenfeld *et al.,* 2016; Hegyi *et al.,* 2019). The most likely explanation for optimal fascicle length adaptations is most probably a combination of all the above-mentioned factors.

When it comes to hamstring strength assessments, short muscle lengths are also generally preferred (Opar *et al*., 2013; Hickey *et al*., 2015; Wollin *et al*., 2016). This may provide some explanation for the varying success of previous exercise interventions and associations between knee flexor assessments and HSI injury risk (Bourne *et al.,* 2018).

Generally, it is proposed that a balanced lateral to medial hamstring force coupling is desirable for healthy functioning (Schuermans *et al.,* 2014). However, long muscle length training with greater hip flexion may selectively stimulate the commonly injured BF_{lh} muscle and tendon (Guex *et al.,* 2012; 2013) and subsequently increase BF_{lh} fascicle length (Guex *et al.,* 2016). Therefore, it is acceptable to believe that directly targeting the BF_{lh} will yield greater injury-preventing benefits. Not doing so may provide some explanation towards the findings of unsuccessful initial and recurrent HSI limitation in recent years.

2.2.4.b. Hip vs. knee dominant training

To enable greater BF_{lh} muscle recruitment and capacity to increase fascicle length, Guex *et al.* (2013)'s conceptual model for HSI prevention suggested hamstring exercise to be performed where the hip is in flexion, where a greater level of hip extension torque is required. This theory has been implemented in various hamstring exercise classification studies in order to understand whether specific hamstring exercises are able to selectively recruit individual hamstring muscles and regions and therefore be suited for specific roles (Mendez-Villanueva *et al.,* 2016; Tsaklis *et al.,* 2015; Bourne *et al.,* 2016; Bourne *et al.,* 2017b; Hegyi *et al.,* 2019; Schoenfeld *et al.,* 2015). Generally, exercises requiring a greater hip extension torque elicit higher lateral-medial recruitment patterns (Tsaklis *et al.,* 2015; Bourne *et al.,* 2016) and preferentially target the proximal regions of the hamstring muscles (Mendez-Villanueva *et al.,* 2016). In opposition, knee flexor biased exercise has been shown to provide greater distal hamstring activation (Schoenfeld *et al.,* 2016). More recent research with the use of high-density electromyography has been less successful in finding such obvious lateral-medial and proximal-distal muscle distribution changes (Hegyi *et al.,* 2019), where only a 45° hip extension exercise saw greater BF_{lh} to ST and proximal-distal activation. Such variation can arise from small changes in exercise prescription such as exercise intensity and of course limitations surrounding surface electromyography (sEMG) data acquisition (Vigotsky *et al.,* 2018). One limitation of such involves specific location of sensor placement, due to the possibility of differential subcutaneous fat levels or muscle fibre positioning beneath the electrode. Research surrounding regional muscle excitation that is completed without high-density electromyography must also be taken with great caution due to the singular muscle excitation point of acquisition. With the above being said, it is also suggested that considering the absolute activation that an exercise elicits on individual muscles is also important, as although the lateral to medial hamstring activation during the Nordic hamstring exercise was low, the absolute activation of the lateral hamstrings was still high (Bourne *et al.,* 2016).

Considering the general consensus of hip dominant hamstring training for BF_{lh} recruitment, it would be feasible to suggest that hip dominant training interventions may also provide superior adaptation to the BF_{lh}. Such theories have been investigated with promising findings of superior BF_{lh} hypertrophy after a 6-week training block of 45° hip extension exercise when compared to the Nordic hamstring exercise (Bourne *et al.,* 2017a). Considering the greater eccentric bias of the Nordic hamstring exercise, similar fascicle length changes between the two groups also provides interesting findings, since the concentric contractions during the 45° hip extension exercise may have a dampening effect on fascicle length changes (Timmins *et al.,* 2016; Franchi *et al.,* 2014).

In order to maintain physical performance levels during a soccer match an athlete's ability to maximise recovery between high intensity efforts is essential (Mohr *et al.*, 2005). The rate at which athletes can maintain this is influenced by several characteristics of fitness; i.e. aerobic and anaerobic energy (Bangsbo *et al.,* 2006) and neuromuscular (Buckthorpe *et al.,* 2014; Marshall *et al.,* 2014) system function. Furthermore, hamstring injury risk increases during the latter stages of competition (Woods *et al.,* 2004), so a means of minimising performance decrements and injury risk are warranted. For the hamstrings in particular, reduced rate of torque (Grazioli *et al.,* 2019) and force (Thorlund *et al.,* 2009) development and an increased angle of peak torque (Cohen *et al.,* 2014) is experienced after subsequent fatiguing soccer exercise. This may contribute towards the reduction in performance and increase in injury risk that are shown. Considering this and alongside methods of improving aerobic and anaerobic fitness, one means of minimising soccer-related fatigue may be the direct training of the hamstrings under a "fatigued" state (Small *et al.,* 2010). Furthermore, hamstring strength endurance training also provides possible benefits to performance and injury via a prevention of eccentric hamstring torque decrements after soccer-specific fatiguing exercise (Matthews *et al.,* 2017). With this in mind, another possible benefit of hip vs. knee dominant training is the presence of its matched or superior effects on the strength endurance capacity of the hamstrings (Rey *et al.,* 2017; MacDonald *et al.,* 2018).

To summarise, it may be suitable to believe that when the goal is to target the BF_{lh} for training and assessment purposes, hip extension biased hamstring exercise should be prioritised, yet evidence is inconclusive.

2.2.4.c. Gluteus maximus functioning as a synergist

Aside specific targeting of the BF_{lh} muscle, hip extension exercise may also directly influence HSI management via increased G_{max} force production and muscle excitation to withstand the high external forces that are present during sprint-acceleration performance (Schuermans *et al.,* 2017a). As a prime mover in hip extension, the G_{max} is required to function as the predominant force generator during sprinting, with the hamstrings required more so as a force transducer (Hoskins & Pollard, 2005). Providing torques of up to and over double that of knee flexion torques during sprinting (Higashihara *et al.,* 2018), increased G_{max} function can reduce the stress placed on the hamstring muscles throughout gait. In a prospective study of HSI in sprinters, poor concentric hip extension torque was found as an indicator of subsequent injury on follow up (Sugiura *et al.,* 2008). In addition, hip extension concentric torque and G_{max} activity at the end-of-swing have been found as two key predictors of horizontal force maintenance during repeated treadmill sprinting (Edouard *et al.,* 2018). This may occur due to a preparation for ground contact and the following concentric action to reproduce force against the floor and may protect the hamstrings from increased lengthening under excessive force. Finally, it is interesting to find that the hamstrings function ahead of the G_{max} to resist lengthening forces under controlled conditions until stress exceeds their capacity (Motomura *et al.,* 2019). However, during times of neuromuscular fatigue (such as repeated sprinting) the G_{max} functioning to take over may become vital when extreme forces are exerted to protect the hamstrings. Therefore, optimal G_{max} functioning may be crucial during the latter stages of competition where soft tissue injuries occur most (Woods *et al.,* 2004; Ekstrand *et al.,* 2009; Brooks *et al.,* 2006).

2.2.4.d. Hip extension on trunk control

Aside having the capacity to produce and absorb force, lumbo-pelvic control has been considered a key factor for the management of HSI (Panayi *et al.,* 2010). Anterior pelvic tilt causes irritation of the hamstring's origin leading to pathology via innervation inhibition (Panayi, 2010) and lengthening of the hamstring muscles by drawing the muscle origins away from the insertion points. Athletes with an anterior pelvic tilt whilst running have been said to be at an increased risk of sustaining HSI due to the relatively longer working length of the hamstrings and reduced activity of the trunk muscles (Schache *et al.,* 2000; Opar *et al.,* 2012; Schuermans *et al.*, 2017a). Anterior pelvic tilt can arise as a result of environmental influences such as sporting biases which in turn influence musculoskeletal factors such as anterior hip capsule tightness (Yerys *et al.,* 2002; Schache *et al.,* 2000; Mills *et al.,* 2015), deficient G_{max} functioning (Tateuchi *et al.,* 2012) and excessive erector spinae neuromuscular activity (Tateuchi *et al.,* 2012; Schuermans *et al.,* 2017b). Within healthy subjects increased ipsilateral erector spinae activity has been associated with a decreased G_{max}:ST activation ratio during prone hip extension (Tateuchi *et al.,* 2012) and reduced passive hip flexor tightness may further reduce G_{max} activation (van Gelder *et al.,* 2015; Mills *et al.,* 2015). Such deficiencies can result in anterior pelvic tilt and reduced G_{max} activity and in turn increased stress on the hamstring muscles.

In order to improve pelvis and trunk control, posteriorly tilting the pelvis during exercise may be favourable due to the increases in G_{max} activation that are evidenced (Kim & Seo 2015; Choi *et al.,* 2015). Furthermore, increases in hip extensor strength have been evidenced to reduce pelvic motion during running (Ford *et al*., 2013).

During the swing phase of running gait, a combination of the above-mentioned factors may induce greater stress on the hamstring muscles due to deficient synergistic force coupling of the G_{max} (Elphington, 2008). This may provide some explanation to the findings of reduced G_{max} activity during the front swing of gait in sprinters sustaining subsequent HSI (Schuermans *et al.,* 2017a). Inefficient trunk control may also lead to excessive "dynamic anterior pelvic tilt" action. This action can be described as an anterior-to-posterior tilt or "jolting" action as the hip flexes at leg cross over (mid-swing), followed by a re-anterior tilt during mid-late swing after the hip has fully flexed. During this phase the knee also begins to extend. Here hamstrings may be exposed to brief stretch due to lengthening at both proximal and distal ends where the muscle rapidly loses and regains tension (Fousekis *et al.,* 2011).

In summary, it is evident that there are several factors that may place the hamstrings at an increased risk of injury during acceleration and sprint performance. Determining the degree to which each risk factor may or may not contribute towards subsequent injury is difficult, but it is clear that optimal functioning of the hip extensor muscles will prove beneficial to the management of many of these factors. Considering the high prominence of these injuries and the injury burden – success link in soccer, management of such factors may be key.

2.2.5. Hip extension and knee ligament injury

As indicated at the beginning of the literature review, soccer is a sport governed by various movement skills. Because of this, the sport also has a high prominence of injuries aside HSI during the HIE of sprint-acceleration. For instance, severe injuries to knee ligaments are common in soccer (Ekstrand *et al.,* 2011) during HIE movement such as COD and jumping (Davies, 2016; Grimm *et al.,* 2015; Alentorn-Geli *et al.,* 2009a). Therefore, it seems suitable at this point to shortly introduce the assisting role that the hip extensors may also play in the prevention of these injuries to provide further evidence for hip extension directed training for injury management in soccer.

2.2.5.a. Knee ligament injury occurrence

Dysfunction of a single joint is suggested to influence the postural balance and performance of the distal joints in the kinetic chain and may cause a severe injury (Steinberg *et al.,* 2017). Generally, injury to the knee occurs when there is a non-favourable force transmission within the muscles and/or translation of bones surrounding the joint. Such occurrences can arise from either kinetic deficiencies such as reduced muscle strength or kinematic deficiencies such as undesirable joint angle displacements during the movement task (Alentorn-Geli *et al.,* 2009a)

2.2.5.b. Knee ligament injury management, kinetics

Generally, strength development is reported as having a preventative effect on knee ligament injury occurrences in soccer athletes (Alentorn-Geli *et al.,* 2009b; Silvers-Granelli *et al.,* 2017). With that being said the kinetics surrounding the occurrence of injury seems to favour the avoidance of increased knee extensor force dominance and looks to promote hip extensor dominance during change of direction and jumping tasks. This is due to the fact that increased reliance of the knee extensor muscles and reduced hip extensor moments is said to increase the stress placed upon the ligaments surrounding the knee (Stearns and Powers, 2014). In addition, it is speculated that a change to a hip dominant strategy enables force to be absorbed sufficiently without increasing the shear load placed about the knee joint (Pollard *et al.,* 2010). For example, weaker hip extensors are found to increase knee extensor reliance during jump landing tasks (Pollard *et al.,* 2010) and the tibial shear force and deficient frontal plane knee stability found jump during landing tasks has been found to be reduced by increased hamstring strength (Lloyd *et al.,* 2001). Furthermore, stronger athletes are generally believed to be able to increase the hip to knee force ratio during the impact phase of a change of direction tasks via increased hip extensor moments (Davies, 2016). This belief has been confirmed after a training intervention where knee adductor moments were reduced, and hip moments increased (Stearns and Powers, 2014). It can therefore be postulated that as the individual becomes stronger, greater loading can be transferred to the hip. As strength continues to increase, the hip may be able to absorb so much of the force that lower contributions can be made by the knee and ACL strain in the sagittal plane can be moderated. Hip focused training programmes have subsequently been recommended to increase transfer to hip moment utilisation during performance tasks (Davies, 2016).

2.2.5.c. Knee ligament injury management, kinematics

Regarding the kinematics of injury, sagittal plane biomechanics have an important role to play in the injury mechanism. Weaker athletes are generally said to present deficiencies of increased knee extensor activity (Pollard *et al.,* 2010) lower hip flexion angle (Davies, 2016) and increased adduction moments and knee valgus (Pollard *et al.,* 2010) during change of direction and jump tasks. Such occurrences are said to place the structure surrounding the knee joint under increased stress where increase likelihood of ligament sprain is present. During the first 50 milliseconds of impact, a more extended knee position is said to be most detrimental to ACL rupture risk (Koga *et al.*, 2010), whereas a more flexed knee is suggested to reduce ACL strain (Davies, 2016). However, findings from Koga *et al.* (2010) must be taken with caution due to the low sample rate 50-60 Hz that the injury instances were videoed and analysed from, which only allows for 1 frame every 20 milliseconds. Furthermore, it seems important to add that directly relating these findings from court-based to field-based sports may be inappropriate due to the obvious differences in footwear and surface conditions that athletes are performing under.

Considering the specific differences in surface friction and footwear, it cannot be confirmed that Low knee flexion during drop landing tasks present a similar picture of increased knee valgus and adductor moments (Pollard *et al.,* 2010). Increased hip flexion is also seen as a vital kinematic of ACL reduction during jump landing tasks (McCurdy *et al.,* 2012) as less hip flexion during drop landings increases the stress placed on the ACL due to less muscular support available to absorb the landing force (Blackburn & Padua, 2009). With regards to cutting angle, the limited amount of research seems to suggest that an increase elicits a greater requirement of knee flexion (Havens & Sigward, 2015), suggesting deeper cutting angles have a larger impact on knee kinematics.

In conclusion, this section confirmed the abundance of support surrounding the kinetics and kinematics of hip extension and implications of training for reducing sprint-acceleration, COD and jump related injuries in soccer. For this reason, it could be suggested that consistent hip extension focused training will provide global benefits to managing and preventing various soccer related injuries and reducing subsequent injury burden. However, injury management is just one area of interest for sports science and medicine departments, where physical performance sits hand in hand to play a critical role in the success of an organisation. As such, it seems relevant at this point to turn to the critical evaluation of physical performance in soccer, specific to hip extension.

2.3. Physical performance in soccer

In a similar format to the injury management section, the following section provides a detailed observation of sprint-acceleration, COD and jumping as individual HIE's required in competitive soccer. In order to do this, the quantification and prevalence of each HIE in soccer is first discussed to understand the specific requirement of each action in the sport. Following this, the physical underpinning of these actions is explained specifically oriented towards hip extension in order to provide a proof of concept and to drive an understanding of suitable training methods for physical development.

2.3.1. Quantification of high intensity efforts

Quantification of HIE's is important to enable practitioners to begin to understand the physical requirements of competition and the exposure of training that athletes undertake at an acute and chronic level. In professional soccer, external load is a term that generally governs the mechanical load imposed on athletes. This can be divided into velocity- and displacement-based variables and both of which make up important considerations for understanding the volume and intensity demands of soccer match play. Methods of assessing external load are generally governed by global positioning system (Buchheit & Simpson, 2017; Cummings *et al.,* 2013), although several other methods of collecting this information are available such as semi-automated tracking systems (Di Salvo *et al.,* 2006; Castellano *et al.,* 2014) and accelerometers (Boyd *et al.,* 2011). With the availability of these tracking systems to explore the physical requirements of sport, practitioners are able to quantify which movement patterns may or may not be most relevant for achieving success.

2.3.2. Prevalence of high intensity efforts

2.3.2.a. Sprint-acceleration

The relevance of sprint-acceleration performance in soccer is heavily documented. On a basic level, sprint performance during competition is often found to differentiate elite and non-elite populations (Haugen *et al.,* 2013), influence match outcome (Andrzejewski *et al.,* 2016; Chmura *et al.,* 2018; Konefał *et al.,* 2019) and is frequently seen to be the most common actions preceding a goal in soccer (Faude *et al.,* 2012). Generally, soccer players cover 5.42 and 0.97 m.min of high-speed running and sprinting distance in a match (Varley *et al.,* 2014) respectively, yet elite level soccer athletes from the English Premier League have been found to produce up to 10.41 and 2.78 m.min, respectively (Bradley *et al.,* 2009). Alongside the ever-increasing competitiveness of the sport, the physical requirements of maximum velocity (Haugen *et al.,* 2013), distance covered at high-speed and sprint velocities and number of sprints are also increasing (Bush *et al.,* 2015; Barnes *et al.,* 2014). With that being said, maximal accelerations have been found to be 4- (Murtagh *et al.,* 2019) and 8-times (Varley & Aughey, 2013) more likely to occur than sprints where up to 90 exposures are found per match (Ingebrigtsen *et al.,* 2015). As such, an argument could be made either way for the prioritisation or bias of acceleration of maximum-velocity related training in soccer, yet both are certainly evidenced as important indicators to success in soccer.

2.3.2.b. Change of direction

Playing dimension restrictions in sport can be said to lend bias towards certain actions. For example, COD's are extremely common and suggested to be a key determinant of court sports such as basketball (Montgomery *et al.,* 2010; Schelling & Torres, 2016). Having said this, changing direction has also been suggested as crucial for success in soccer, where overcoming even a short space of ground on your opponent may lead to a goal scoring or stopping opportunity (Carling *et al.,* 2008; Brughelli *et al.,* 2008). These actions occur multiple times every minute in team sports (Bloomfield *et al.,* 2007; Gabbett *et al.,* 2008) and 10-12% of can be classed as explosive or of a high intensity (Bloomfield *et al.,* 2007). Regarding the severity of angles during COD, soccer play may require athletes to complete full 180º cuts for instance when a ball travels past a player and they must perform a recovery run in an attempt to regain possession. In addition, smaller angles of directional change may also occur when attempting to dribble past opponents when in possession of the ball. As such, the physical underpinning of COD actions is largely dependent on the situation and condition of the directional change.

2.3.2.c. Jumping

Aside ground-based duels of racing for the ball or gaining an extra yard on your opponent aerial duels are also frequent in soccer (Kennedy & Drake, 2017). Vertical jumping actions are commonly found to precede goalscoring opportunities (Faude *et al.,* 2012) and are an important technical and physical quality for soccer players that is perhaps position and tactic dependent. As such vertical jump capacity is commonly assessed in the sport (Malone *et al.,* 2015; Claudino *et al.,* 2017) and is a recognisable feature of strength and conditioning programs, perhaps partly due to the similarity of SSC's that are found to be performed in a match (Oliver *et al.,* 2008). However, at this point it seems suitable for the research team to provide an aware of the recently presented limitations surrounding vertical jump height as an indicator of vertical power. Here the factors of body mass, push-off distance, optimal loading and the force-velocity profile may explain discrepancies between the two (Morin *et al.,* 2019). An awareness should also be given to the individual differences in jump strategy that may influence the force-time characteristics of a jump. For example, a shallower countermovement with steeper rise in force and shorter time frame will incur concurrent increases in peak power and take-off velocity, and consequently, jump height (Chavda *et al.,* 2017). As such, future investigations may wish to look at alternative variables within vertical jumping such as eccentric and concentric contraction times alongside force-velocity relationships (Chavda *et al.,* 2017).

Interestingly, vertical jumps are not seen to differentiate between playing standard (Castagna & Castellini, 2012; Sporis *et al.*, 2009) and are not improving over time (Haugen *et al*., 2013). Possibly, these findings can be partly attributed to the horizontal oriented direction that soccer biases (Murtagh *et al.,* 2019) which also explain greater interest of horizontal jump development and assessment in recent times (Lockie *et al.,* 2016; Murtagh *et al.,* 2017; 2018). Such horizontal jump assessments have been found to differentiate between playing standard in soccer (Murtagh *et al.,* 2017) perhaps due to their similar physical determinants to maximal acceleration (Dobbs *et al.,* 2015).

2.3.3. Physical underpinning of high intensity efforts

The attributes that underpin physical performance are of course movement specific and require a combination physical and biomechanical variables in coordination to ascertain success. In this case, movement kinetics can describe the internal and external force contribution towards movement and movement kinematics seek to explain the motion of the musculoskeletal system through joint actions. The holistic development of high intensity actions such as sprint-acceleration, change of direction and jumping is perceived to be inclusive of several factors surrounding movement technique, strength and power training, speed work and energy system development (Haugen *et al.,* 2019; Nygaard *et al.,* 2019). However, when looking more specifically at the relative contribution of individual muscles and joint actions towards an athletic movement, they are generally deemed vector and intensity (velocity and load) dependent (Beardsley & Contreras, 2014). As such, the hip extensors and knee flexors are more associated with movement in the forwards direction (Morin *et al.,* 2011; 2014; 2015a; 2015b; Edouard *et al.,* 2018; Bartlett *et al.,* 2013). Therefore, it could be said that hip extension is crucial for acceleration and maximal sprinting performance. Having said this, hip extensor functioning has also been associated with change of direction and jumping performance, as the following text will explain. In addition, the association between HIE and hip extensor muscle involvement is generally seen to strengthen alongside exercise intensity

(Beardsley & Contreras, 2014) during gym-based exercise (Bryanton *et al.,* 2012; Riemann *et al.,* 2012; Swinton *et al.,* 2011), running (Schache *et al.,* 2011), changing direction (Inaba *et al.,* 2013) and jumping (Lees *et al.,* 2004). Therefore, it could be said that a hip extensor focus of training may be adopted when improving HIE capacity is the goal. As such, the remainder of this section seeks to investigate the kinetic and kinematic underpinning of the HIE's introduced above to present a rationale for hip extension focused training.

2.3.3.a. Sprint-acceleration

i. Kinetics related to external forces

In general, acceleration- and sprint- actions share similar kinetic and kinematic attributes. During both instances, horizontal ground reaction force (GRF) is required in order to achieve forward propulsion of the body's centre of mass (COM) and vertical GRF is required in order to maintain upright against the effects of gravity. At early acceleration, great emphasis is placed on horizontal GRF due to increased availability of time during contact to produce force in that direction (Wild *et al.,* 2015; Dorn *et al.,* 2012). As such, acceleration is generally related to an increase in horizontal force production to a greater extent than vertical force (Brughelli *et al.,* 2011; Buchheit *et al.,* 2014; Morin *et al.,* 2011; 2014; 2015; Otsuka *et al.,* 2014). In order to achieve such high amounts of horizontally oriented GRF, Morin *et al.* (2014) indicated that individuals must have strong hip extensors and/or be able to activate them in an effective way.

ii. Kinetics related to internal forces

During sprint-acceleration the hip joint extends throughout the entire stance phase which allows for a great potential for hip extension torque. As previously alluded, this potential torque may become even more relied upon as action intensity increases (Beardsley & Contreras, 2014; Bartlett *et al.,* 2013). Hip extension also seems to be the only joint action of the lower limb that doesn't shift dominance from a concentric to isometric/eccentric action as acceleration turns to maximum-velocity sprinting (Wild *et al.,* 2015). This would suggest that the hip extensors continuously contribute towards positive horizontal propulsion when running, whereas other muscles may solely act to minimise energy loss or decelerative forces (Kyröläinen *et al.,* 1999; Morin *et al.,* 2014). A hip extensor dominance during running can also be confirmed via electromyography (EMG) studies as evidenced in the comprehensive review by Howard *et al.* (2017). In addition, as running speeds progress from 3.5 and 9.0 ms^{-1} a 304% increase in total hip extensor activity has been found (Schache *et al.,* 2011), which has been said to partly explain the increase in force production (Kyröläinen *et al.,* 1999). The sEMG activity of the G_{max} in particular increases 5-fold from walking to a sprint (Bartlett *et al.,* 2013) where it functions heavily during ground contact to reproduce accelerative horizontal forces against the floor (Bartlett *et al.,* 2013). In addition, hamstring sEMG kinetics are seen to increase alongside running intensity (Chumanov *et al.,* 2007; Higashihara *et al.,* 2010) but are greatest in the late-swing phase (Chumanov *et al.,* 2007; Schache *et al.,* 2012) or early stance phase (Yu *et al.,* 2008) to resist unwanted lengthening. This information again reiterates suggestions of the hip extensors holding a lead role for force production during sprint-acceleration performance.

iii. Kinematics

Regarding kinematics, running gait analysis is generally made up of variables related to step length, step frequency, ground contact time (GCT) and flight time. Such variables coexist within maximal acceleration and sprint performance at different levels and define the time, displacement and velocity parameters required for successful performance. In order to accelerate, increasing force application must be combined with either an increase in step frequency or GCT and is dependent upon the phase of sprint-acceleration performance. Therefore, the hip extensor muscles may have differentiating functions as running speed progresses. As there appears to be a distinct separation, the remainder of this sub-section seeks to understand where hip extension exists within the individual interrelations of kinetic and kinematics for acceleration and sprint performance.

iv. Individual determinants of acceleration

The goal of the maximal-acceleration phase of sprinting is to displace the body's COM as far as possible in the shortest amount of time. In order to do so, great amounts of impulse (force*time) are to be accomplished upon ground contact. During initial-acceleration, GCT's are pronounced and reduce as the phase continues towards maximum-velocity (Wild *et al.,* 2015). Because of the greater GCT present in acceleration, it seems that there is a greater opportunity for increasing horizontal impulse during initial acceleration via increased hip extensor force application. This has been evidenced where hip extension torque (Higashihara *et al.,* 2017) and horizontal GRF (Rabita *et al.,* 2015) has been found to be significantly greater in the early stance phase of acceleration than of sprinting. In combination with a greater forward lean of the trunk, this can explain the large bias towards horizontal force production (Buchheit *et al.,* 2014; Loturco *et al.,* 2018) and hip extensor activity (Higashihara *et al.,* 2017) that acceleration is evidenced to have. This has also been confirmed by Buchheit *et al.* (2014) who found horizontal force to be a key determinant for maximal-acceleration performance in soccer players (Buchheit *et al.,* 2014), and by others who determined horizontal impulse (Morin *et al.,* 2014) and propulsion (Nagahara *et al.,* 2018) to be highly associated with maximal acceleration. Finally, Morin *et al.* (2012) deemed the ability to apply a greater forwards resultant GRF during acceleration to be a main determinant of 100 m sprint performance. This bias has also been evidenced in research by findings of a greater relationship between horizontally (hip thrust) vs. vertically (loaded and unloaded jumps) biased exercises to sprint acceleration (0-40 m) performance in sprinters (Loturco *et al.,* 2018). The information presented here can be interpreted as a recommendation for hip extensor focused strength and power training, in order to improve horizontally oriented force application and in turn enhance acceleration performance.

v. Individual determinants of sprinting

When looking at maximum-velocity sprinting, GCT's are reduced and stride frequency is increased (Wild *et al.,* 2011) which may be partially due to an inability of the lower limb extensors to generate sufficient vertical force to spend a longer period of time airborne. Braking forces during ground contact are also seen to increase during sprinting (Salo *et al.,* 2008), where suppression of these forces towards maximum velocity is highly associated with sprint performance (Nagahara *et al.,* 2018). When braking forces equal propulsive forces at maximum-velocity, a plateau acceleration occurs (Wild *et al.,* 2011). Both horizontal and vertical GRF increases alongside running intensity (Higashihara et al., 2017; Brughelli et al., 2011), yet only horizontal force is significantly greater at maximum velocity than at 60 and 80% of maximum velocity, (Brughelli et al., 2011). With that being said, vertical forces remain to be approximately 5-fold greater than horizontal forces at 100% maximum velocity (Brughelli et al., 2011). Loturco *et al.* (2018)'s findings would suggest that vertically oriented exercises are more associated with maximum-velocity sprinting, yet Morin *et al.* (2015) suggested that those who are able to "push more" and "brake less", prioritising horizontal force, have been found to be superior sprinters. Therefore, it seems as though orientation of total force (more horizontal) applied is more important to performance than its amount and the ability to limit the decrease in ratio of force (horizontal: vertical) and is highly correlated with 100 m sprint times (Morin *et al.,* 2011).

To conclude, successful sprint-acceleration performance seems be heavily reliant on the hip extensor muscles because of the increased GRF requirements in the vertical and specifically horizontally direction. Alongside the correlations and associations discussed in this section, this may also explain some of success that has been evidenced from hip extension directed training interventions for sprint-acceleration improvements in the past (Contreras *et al.,* 2017; Brown *et al.,* 2017; González-García *et al.,* 2019; Neto *et al.,* 2019; Abade *et al.,* 2019). As such, these methods should be considered by practitioners when planning specific training interventions to develop sprint-acceleration performance in soccer. Successful adherence may directly influence an athlete's capacity to repeat HIE in competition and in turn improve the chance of success.

2.3.3.b. Change of direction

Successful and safe change of direction performance is determined optimal biomechanical movement of the upper and lower limbs to ensure the specific interaction of the body's COM, joint angles and torque about such joints is efficient. The multidirectional nature and unorthodox circumstances found during changing direction may render it a more difficult action to break down with respect to kinetic and kinematic requirements. A directional change may in theory describe a small alteration in body orientation during a constant speed such as an arching run or a complete manipulation of direction and velocity as often performed by wide players in soccer in an attempt to lose their opponent. For that reason, the kinetic and kinematic variables associated with external forces, muscle requirements and movement variation found during these actions may be substantially varied. Generally, training interventions with a view to improve change of direction performance and reduce injury risk during these instances are inclusive of sprint, strength and power and COD specific training (Brughelli *et al.,* 2008). Generally, the success of these training interventions are varied and perhaps down to the lack of specificity of exercise selection (Brughelli *et al.,* 2008). As such, the remainder of this section will focus specifically on how hip extension may be important for changing direction under conditions deemed a HIE.

i. Kinetics related to external forces

Upon changing direction, it would be expected that both horizontal and vertical GRF increases alongside action intensity. During the deceleration phase that often initiates a change in direction, negative horizontal GRF is expected to be large to reduce momentum of the body to enable the reorientation of the COM in the direction of interest. The same may be suggested for vertical GRF where the body is required to resist an excessive displacement or velocity change of the COM in the vertical plane. To the researcher's knowledge, literature surrounding this topic is unfortunately sparse. During reacceleration after the initiation of the directional change, great horizontal propulsion is suggested to be required (Hunter *et al.,* 2005). Depending on the drop in vertical displacement of the COM during deceleration, a large reacceleration in the vertical plane may also be required. Therefore, this information would suggest that the hip extensors may contribute throughout the whole cycle of changing direction in order to handle the deceleration and reacceleration driven forces that are experienced.

ii. Kinetics related to internal forces

Generally, the G_{max} alone and G_{max} and hamstrings have been found to be responsible for the upkeep of bodyweight support (vertical GRF) and deceleration and acceleration in the horizontal plane, respectively (Maniar *et al.,* 2019). Deceleration is generally suggested to place great mechanical and metabolic load on the knee extensors (Rand & Ohtsuki, 2000; Havens & Sigward, 2015), yet, the hip extensors also function through eccentric contraction in order to assist the muscles surrounding the knee to absorb force (Malinzak *et al.,* 2001; Hader *et al.,* 2016). During stance as the directional change begins, the G_{max} specifically has been found as the dominant contributor to vertical support (Maniar *et al.,* 2019). Extension of the hip is then suggested to be heavily relied upon during the reacceleration phase of changing direction in a similar format to linear acceleration described previously. Interestingly, greater activity of the hamstrings has been found during change of direction tasks in comparison to linear running (Hader *et al.,* 2016; Besier *et al.,* 2003) and faster 45° cutting tasks have been associated with greater hip sagittal power and hip extensor moments (Havens & Sigward, 2015). In addition, Inaba *et al.* (2013) presented hip extension torque and not hip abduction torque to contribute significantly to increasing distance during a side-stepping task. Similar findings have also been found during lateral cutting manoeuvres where maximal hip extension velocities led to better performance (Shimokochi *et al.,* 2013). Therefore, it comes as no surprise that the hip extensors have been found as the primary contributors to propulsion during the first 60% of reacceleration during stance (Maniar *et al.*, 2019).

iii. Kinematics

Regarding the kinematics of changing direction, velocity and cutting angle (°) have been described as the critical factors that influence technical execution (Dos'Santos *et al.,* 2017). Generally, an increase in cutting angle will result in greater deceleration and reacceleration requirements, increased magnitude of braking and propulsive forces, orientation of force vector, joint and segmental positioning and lower limb muscle activity. Such information is beyond scope of this review but is comprehensively discussed in work from Dos'Santos *et al.* (2017). However, of relevance to this review, greater cutting angles induce greater posterior GRF (horizontal plane) during the braking phase (Havens & Sigward, 2014; Jones *et al.,* 2017; Dos'Santos *et al.,* 2017), greater trunk flexion during stance (Havens & Sigward, 2015) and increased BF_{lh} muscle activity across the deceleration and reacceleration phase (Hader *et al.,* 2016). It would be expected that such findings suggest an increase in contribution of the hip extensors towards force absorption and production. Increased hip flexion occurs in order to cope with the greater GRF placed on the lower limbs upon greater cutting angle and approach velocity (Havens & Sigward, 2015). Increased hip flexion may also remain present during directional change itself in order to cope with a greater COM displacement required for larger alterations in movement path. This could also be coupled with greater contact times when cutting angle is increased (Havens & Sigward, 2015). Finally, having to complete change of direction in a shorter space of time will decrease reacceleration times. This in turn may require the hip extensors to produce more force in a shorter timeframe to re-extend the hip from its flexed position found during the change of direction phase itself.

In summary, the hip extensors are suggested to play an important role during the deceleration phase of directional change to limit excessive stress on the knee joint and muscle surrounding it. During changing direction, an increase in approach speed, cutting angle and reacceleration speed will place greater emphasis on hip extensor recruitment in order to cope with the increased mechanical and metabolic load during eccentric contractions. Reacceleration of the COM may then be suggested as the most crucial phase for the hip extensors to act concentrically where they are heavily required during the horizontal propulsive action. As such, greater improvements in COD ability have been found after plyometric based horizontally oriented exercise (horizontal jumps and drop jumps) interventions when compared to vertical oriented exercise (vertical jumps and drop jumps,) interventions (Gonzalo-Skok *et al.,* 2019; Dello Iacono *et al.*, 2019). Evidence also lends improvements in COD from combined formats of training (Keller *et al.,* 2018), where a combination of the abovementioned facets will be exercised. Regarding resistance training for improving COD performance, the evidence for vertical oriented / axially loaded training (olympic lifting, squats, deadlifts) is inconclusive (Brughelli *et al.,* 2008; Zweifel *et al.,* 2018) and investigations of horizontally oriented / anteroposterior loaded resistance training for COD improvements are absent.

2.3.3.c. Jumping

As indicated in the above section on the prominence of jumping in soccer, a multidirectional nature is also present for jumping tasks. This will in turn influence the kinetic and kinematic requirements of the hip extensor muscles when contributing to performance of jumping tasks.

i. Kinetics related to external forces

As it would be expected, jumping in various planes places a dominance upon specific force vectors that contribute to the movement. Similarly, to the COD section, the multidirectional nature of soccer maintains jumping in the vertical, horizontal and lateral plane (Murtagh *et al.,* 2017). Vertical jumping objects to displace the body's COM in the vertical plane and as such requires great a vertical force vector dominance (Schache *et al.,* 2014). This can be found where peak vertical power has been found to explain 61 and

65% of the variation in bilateral and unilateral vertical jumps (Murtagh *et al.,* 2017) and vertical ground reaction force is greater in vertical than horizontal jumping (Meylan *et al.,* 2010). Horizontal jumping however requires a dominance of horizontal force vectors whilst maintaining a vertical force vector in order to remain elevated from the floor. For instance, peak horizontal power has been found as the best predictor of horizontal jump performance in soccer players (Murtagh *et al.,* 2017) and various team sport athletes (Meylan *et al.,* 2010). Horizontal force during jumping has also been found to have a greater relationship than vertical jumping with performance tasks such as sprinting (Dobbs *et al.,* 2015; Maulder & Cronin, 2005; Meylan *et al.,* 2009) and although weak, change of direction (Meylan *et al.,* 2009). It is likely that horizontal jumping and accelerating share similar force vector requirements and have increased relevance to soccer specific actions. Therefore, assessments of horizontal power have been suggested to have greater face validity than its vertical counterparts (Dobbs *et al.,* 2015). Because of this and the relatedness to the hip extensors, horizontal jump tasks will be a crucial focus of the remainder of this section.

ii. Kinetics related to internal forces

Hip extension is generally seen to play a greater involvement for jumping tasks in the horizontal direction (Nagano *et al.,* 2007; Murtagh *et al.,* 2017) and vertical jumping tasks seem to be more commonly associated with the knee and ankle extensor muscles (Chang *et al.,* 2015; Schache *et al*., 2014). This muscle specific bias may be partly due to the lesser reliance and smaller degree of hip flexion that vertical jumping requires (Nagano *et al.,* 2007). However, vertical jumping remains to elicit increased hip extensor net joint moment upon greater jump heights (Chiu *et al.,* 2014) and can be explained by a greater degree of hip flexion present during the downwards phase of higher vertical jumps (Lees *et al.,* 2005). During skeletal modelling, substantially higher hamstring work has been found during the downwards phase of horizontal jumping, suggesting a bias towards eccentric contraction or negative work (Nagano *et al.,* 2007). With that being said, increased biceps femoris activation was also found during the upwards or "push-off" phase of the horizontal jump (Nagano *et al.,* 2007). Within elite and sub-elite youth soccer players, greater BF_{lh} activation has been found during both downwards and upwards phase of unilateral horizontal jump tasks, in comparison to vertical and medial jump tasks

(Murtagh *et al.,* 2017). It seems that similarly to COD, horizontal jumping requires contribution of the hip extensors throughout the whole movement cycle.

iii. Kinematics

Jump task kinematics can be dissected into individual joint segment angles and velocities. Generally, it is found that horizontal jumping holds an extended duration of total movement than vertical jumps (Nagano, 2007), where the hips undergo a greater range of motion through flexion and extension (Fukashiro *et al.,* 2005; Nagano 2007). The smaller hip joint motion in vertical jumping may be explained by the orientation of the trunk and near-zero angular velocity of the hips at take-off, required for a straight torso in vertical jumping (Pandy *et al.,* 1990). During horizontal jumping however, trunk lean in the forwards direction at take-off is large in order to produce a great horizontal propulsive action (Fukashiro *et al.,* 2005). This greater trunk lean and hip flexion is similar to that of changing direction and accelerating noted above, which explains the heavy reliance of the hip extensors during horizontal jump tasks.

To summarise the HIE of jumping, it seems that the hip extensors play a role throughout the full cycle of jump execution. As it did for COD performance, the intensity, type and timing of hip extensor contribution may vary for different types of jump. There is a strong relationship between horizontal jumping and acceleration (Dobbs *et al.,* 2015) and there is substantially greater frequency of acceleration actions in soccer when compared to vertical jumping (Murtagh *et al.,* 2019). Therefore, a focus towards horizontal jumping training methodologies incorporating hip extension actions may be seen as appropriate for the physical development of soccer athletes.

To conclude, the prominence of HIE in soccer is evident and their presence as causal indicators to physical performance is strongly proven. The specific avenue of hip extension as a dominant joint action for the performance of these HIE looks to be substantial and could be issued great importance by practitioners within the field. When coupled with the potential injury management benefits during sprint-acceleration, COD and jumping movements, hip extension training may provide a dual-effect in improving two key constructs required for success in soccer, physical performance and injury management. Therefore, having the ability to understand individual athletes' hip extension capacity could be an important addition to the toolbox of measures that are collected by sports science and medicine departments.

2.4. Assessing hip extension as a joint action

In order for practitioners to improve their knowledge on the athletic profile of their athletes' physical assessments are often carried out to supplement needs analyses for future training prescription. Follow up assessments on a regular basis is also fundamental to understand athletes' individual capacity to cope with the demands of their sport. As such, it seems important at this point to investigate strength assessments and build a rationale for hip extension assessment in particular. Otherwise, future exploration of hip extension strength for physical performance and injury management may become hard to quantify.

In the final section of this literature review, a discussion of strength assessment is presented and a rationale for the isolation of hip extension strength assessment is built. Five key considerations surrounding the assessment of strength are introduced in the following order; why assess strength (2.4.1), strength assessment fundamentals (2.4.2), how to assess strength (2.4.3), what is being assessed (2.4.4) and where is it being assessed (2.4.5). In 2.4.1, a reiteration of the importance of strength (and specifically hip extension strength) and where it is required in soccer is presented. Then, the fundamentals of strength assessment inclusive of validity and reliability are presented (2.4.2) and the various methods of assessing strength in general and specific forms are discussed (2.4.3). At this point, advantages of specific assessment forms and disadvantages of general assessment forms begin to shape a rationale for targeted hip extension assessment. In 2.4.4, the transferability of strength assessment and training to athletic performance is discussed where reference to the dynamic correspondence and force-vector theories is made, and various facets herein may provide supplementary evidence for hip extension isolation. Succeeding this, the environmental constraints of soccer and how they may favour the selection of a specific assessment tool is discussed (2.4.5). Finally, a rationale is built for the development of a new assessment tool to specifically assess maximal isometric hip extension strength (2.4.6).

2.4.1. Importance of strength in soccer

2.4.1.a. The underpinning of explosive movement and maximum force

Strength can be defined as the maximal force generating capacity of skeletal muscle yet is regularly used as an umbrella term for anything that significantly taxes the musculoskeletal system. Maximum force is underpinned by neural and architectural factors, which can both be improved with specific modes of training. Neural adaptations to training that can improve maximum force of a muscle include central drive, decreased antagonist co-contraction and increased neural firing rate (Folland & Williams, 2007; Gabriel *et al.,* 2006). Architectural adaptations generally encompass fibre growth and thus increased muscle cross sectional area (hypertrophy via pennation angle or fascicle length) and muscle fibre type shifts (Abernethy *et al.,* 1994; Folland & Williams, 2007; Timmins *et al.,* 2016).

Longstanding beliefs, differences in opinion and several environmental and cultural philosophies shape the perceived importance of muscle strength for sports science and medicine teams. With that being said, Newton's second law explains the effectiveness of strength training, whereby if you improve force, acceleration must increase if mass remains the same (F=m*a). In addition, rate of force development (RFD) and external mechanical power are two factors generally deemed essential for explosive movement. Rapid movements require high impulse (Impulse=F*t) and acceleration, whereby an increase in RFD allows for a greater time for force production, thereby improving impulse or reducing the epoch during a given task. Therefore, it comes as no surprise that RFD is largely considered to maintain large relationships with sports performance indicators such as jumping, sprinting and changing direction (Suchomel *et al.,* 2016).

In order to improve RFD and impulse, a review article states that strength training increases generally have a strong relationship with improved RFD, where strong individuals are generally found to produce better RFD than their weaker counterparts (Suchomel *et al.,* 2016). Furthermore, strong athletes generally also have large associations with external mechanical power (Suchomel *et al.,* 2016) so strength can be considered as the foundation for which to build external mechanical power on.

2.4.1.b. Relationship between strength and physical performance

On reflection of the above, the importance of a sufficient baseline level of strength to produce high levels of force is generally accepted (Stone *et al.,* 2002) and there is a considerable body of evidence to suggest that maximal strength levels are largely associated with physical performance (Suchomel *et al.,* 2016). For example, 59, 65, 60 and 83% of maximum strength measures are largely correlated with jump, sprint, change of direction and sport-specific (i.e. cycling, throwing etc.) performance, respectively (Suchomel *et al.,* 2016). Of the studies reviewed in this paper, measures of maximal strength are generally inclusive of 1- or 3-repetition maximum barbell back squat or half squat, olympic weightlifting and their derivatives and bench press exercises, and measures of back squat or mid-thigh pull isometric-strength (Suchomel *et al.,* 2016). Information surrounding the relationship between isolated hip extension strength measurements, such as the barbell hip thrust, and physical performance markers are much less readily available. However, in a sample of elite sprinters (n = 16), Loturco *et al.* (2018) evidenced a very large to nearly perfect relationship between mean propulsive power during a barbell hip thrust exercise and sprint times over 10 to 150 m. Similar associations were also found for the squat jump, countermovement jump, half squat and jump squat exercises in the same study. In addition, Williams *et al.* (2018) found a large significant relationship between peak force produced during a barbell hip thrust and peak sprint velocity ($r = 0.69$, $P = 0.014$). Interestingly, there were no significant correlations for peak force during the bilateral squat ($r = 0.52$, $P = 0.086$) and unilateral split squat ($r = 0.53$, $P = 0.076$) exercises with peak sprint velocity (Williams et al., 2018). Aside this, it has also been found that targeted hip extension exercise provides acute performance enhancing benefits to subsequent sprint performance (Dello Iacono et al., 2018; Dello Iacono & Seitz, 2018). This further implies a close association of heavy-load hip extension exercise and physical performance.

As well as significant baseline levels of strength, increases in lower-body strength are generally found to correlate with improvements in HIE performance in various populations (Seitz *et al.,* 2014; Suchomel *et al.,* 2016). Of the 15 studies presented in a review article by Seitz *et al.* (2014), it was explained that an increase in squat strength generally holds very large significant correlations ($r = -0.88$, $P \leq 0.001$) with a decrease in sprint time. In youth athletes alone, a meta-analysis revealed greater effects of strength training on sprint and jump performance in children vs. adolescent and untrained vs. trained individuals (Behm *et al.,* 2017). Regarding isolated hip extension strength training on sprint performance Neto *et al.* (2019) presented four studies, two of which exhibited improvements in sprint performance (Contreras *et al.,* 2017; Zweifel *et al.,* 2017) and two of which did not (Bishop *et al.,* 2017; Lin *et al.,* 2017). More recently, Abade *et al.* (2019) and Gonzalez-Garcia *et al.* (2019) presented significant improvements in sprint times after hip extension directed training, whereas Jarvis *et al.* (2019) found no significant improvements. As such, it remains inconclusive as to the specific improvement of sprint performance after isolated hip extension training.

2.4.2. Fundamentals of strength assessment

For an assessment tool to provide useful information to practitioners it must be robust in the data that it provides. Therefore, the validity and reliability of an assessment tool are two crucial factors important to consider in this case. Validity has been defined as the ability of the assessment tool to reflect what it is designed to measure (Atkinson & Nevill, 1998) and is often viewed as the preliminary factor requiring investigation. Various forms of test validity have been suggested in the past and are reviewed well by Impellizeri and Marcora et al. (2009). Generally, criterion validity is viewed as the “traditional” form of validity as it involves comparing a new assessment tool to the “gold-standard” via correlation. Such analysis may be useful when availability to the gold-standard measure is not possible or is unsuitable, such as the use of isokinetic dynamometers for analysing large cohorts within a short period of time. In respect to this section, validity maintains an important consideration as practitioners must have confidence that the assessment tools closely represent what they purport to.

Once adequate test validity has been confirmed, is it then logical to seek an understanding of its ability to reproduce the same data under the same conditions, deemed test reliability (Atikinson & Nevill, 1998). Sufficient assessment tool reliability is required to enable practitioners to realise when changes in performance are meaningful and not just a result of the error that comes with measuring the capacity of interest. Random error explains the variation in test reliability that is due to inconsistencies surrounding in assessment setup, implementation and general variability in electronics within test equipment. A second form of error is systematic bias which is the explains error that arises from variables surrounding athlete fatigue levels, motivation and learning effects. Therefore, it is essential that careful consideration is taken when carrying out procedures of assessment setup, athlete familiarisation and timing of data collection to enable the greatest chance of limiting assessment tool error. In order for an assessment tool to hold sufficient validity and reliability, several considerations must be made when designing and utilising such tools. A comprehensive breakdown of these considerations specifically tailored to hip extension is included within the first chapter of the experimental section (chapter 3). At this point, it seems relevant to discuss more global considerations surrounding strength assessment and as such, is presented below.

2.4.3. Types of strength assessment

A fundamental requirement of assessing maximal strength of a muscle is to ensure that a measurement of maximal voluntary contraction is elicited and recorded. Without this, a strength assessment tool cannot be labelled as a measure of the maximal force generating capacity of a muscle. In order to determine maximal strength, traditional measures require collection of 1 repetition maximum scores during dynamic and integrated tasks such as the back-squat or deadlift exercise. More recently, other forms of strength assessment that represent more static and isolated actions have been introduced which may or may not be better suited for purpose. As such, it seems suitable to introduce both general and specific measures of maximal hip extension strength at this point.

2.4.3.a. Dynamic (concentric and eccentric) and static (isometric)

i. General characteristics of assessment

Dynamic measures of maximal strength are governed by contraction under conditions of changing muscle length and examples may include a concentric contraction with isokinetic dynamometry. These changes in length may occur by either shortening (concentric) or lengthening (eccentric) of sarcomeres within the muscle and represent the maximal voluntary contraction of a muscle across a given range of motion. One advantage to dynamic measures is their representation of maximal strength during movement and across a large range of motion, which may provide useful information when determining factors relating to angle of peak force. Secondly, dynamic measure may also be more representative of muscle actions during sport specific tasks considering almost all sporting actions require either a shortening or lengthening of muscles.

ii. Specific characteristics of assessment

However, during assessments holding a dynamic nature maximum force expression is somewhat dependent on factors such as velocity and inter- and intra-muscular coordination, both of which can impact upon the expression of maximum force (Jacobs *et al.,* 1992). Furthermore, the final outcome of several measures of maximal dynamic strength are also dependent on the ability to control for joint angles and velocities and range of motion, each of which are difficult to closely standardise between and within athletes. An instance where joint angle, velocity and ROM may influence the score validity presented in a maximal strength test is during the eccentric knee flexor assessment assessed via tools such as the NordBord (VALD Performance Pty Ltd, Newstead, Australia) and KangaTech (KangaTech Pty Ltd, North Melbourne, Australia). Standardisation of hip angle, eccentric duration and position at which peak torque is required are hard to achieve and monitor, which may lead to inconsistent results.

In order to achieve the desired goal of a true maximum force reading, measurement tools must have the capacity to isolate that individual capacity in controlled and stable conditions. For this reason, isometric contractions are viewed as preferable. Isometric contractions generally hold increased stability allowing a greater potential for maximum force to be produced, as is found in literature (McBride *et al.,* 2006; Behm & Anderson, 2006; Zemková *et al.,* 2016; Behm *et al.,* 2015).

iii. Muscle damage and perceived soreness

It is generally understood that dynamic exercise also provides a greater potential for muscle damage. Research surrounding muscle damage / soreness in response to isometric training is less readily available, yet it is generally believed that the magnitude of damage and soreness is less than during dynamic exercise (Philippou *et al.,* 2004; Jones *et al.,* 1989; Clarkson *et al.,* 1986) and is even less present during short vs. long muscle length isometric contractions (Jones *et al.,* 1989; Allen *et al.,* 2018).

The presence of greater muscle damage and soreness after dynamic (and especially eccentric) exercise can be explained by several factors (Clarkson *et al.,* 2002). As muscles lengthen during the eccentric phase of dynamic exercise, the ability to create greater tension increases and a higher load is distributed across the same number of fibres, resulting in a greater load per fibre ratio (Enoka, 1996; Howell, 1995). In addition, the discharge rate and pattern of neuromuscular activity of motor units is more variable during eccentric contractions than isometric, which can predispose the muscle to greater degrees of strain and damage (Enoka *et al.,* 2001). Furthermore, it is said that increased mechanical strain after dynamic exercise leads to damaged capillary endothelium (Jones & Round, 1997) and in turn a greater degree of inflammation (MacIntyre *et al.,* 1995;

90Smith *et al.,* 1989). Finally, eccentric exercise has been associated with high levels of glycogen utilisation and a delay of resynthesis (O'Reilly, 1987), perhaps related to the greater disturbance to muscle homeostasis that it instigates. Although not confirmed, it is assumed that isometric contractions would not cause such disturbance, so may be less energy-cost to the system.

For the reasons outlined above, *static* measures of maximal strength are often introduced which require muscle contraction in isometric conditions, minimising the risk of physiological stress (Allen *et al.,* 1985). Examples of these specifically targeting hip extension include isometric MVIC's with isokinetic dynamometry (Julia *et al*., 2010; Keep *et al*., 2016; Meyer *et al*., 2013) and portable fixed dynamometers (Nadler *et al.,* 2000; Scott *et al.,* 2004; Thorborg *et al.,* 2013; Kollock *et al.,* 2010). As such, research and application of strength assessment surrounding the use of *static* measures has become more commonplace within the applied setting (McGuigan *et al.,* 2008; West *et al.,* 2011; Silva *et al.,* 2018).

iv. Crossover of dynamic and static assessments

An uncertainty that often comes with the use of isometric training or assessment is the perceived lack of crossover to / representation of dynamic performance. It may be believed that considering almost all athletic movements require a combination of muscle shortening and lengthening, exercising under conditions of a static muscle is suboptimal. Having said this, research to date generally confirms a strong association between isometric strength and dynamic performance (Juneja *et al*., 2010; Lum *et al.*, 2020; Lum & Barbosa, 2019). In a previous systematic review, most measures of isometric strength inclusive of isometric mid-thigh pull (IMTP), individually isolated muscles, isometric squat and isometric bench press hold moderate to strong correlations with both dynamic strength indicators and dynamic performance variables (Juneja *et al.,* 2010). More recently, another systematic review presented similar findings with, alongside further associations with more specific sporting movements such as sprint kayaking and cycling (Lum *et al.,* 2020).

2.4.3.b. Integrated and isolated

Aside the motion differences during strength assessment another categorisation that may separate assessments tools from one another is the degree of integration or isolation that the measurement setup requires. For example, integrated measures of maximal strength generally require muscular effort from several muscles across several joints such as 1 repetition maximum barbell squats. In opposition, isolated measures generally assess the maximal force generating capacity of single muscles across a single joint such as 1 repetition maximum barbell hip thrusts. One advantage of integrated measures of muscle strength is the greater requirement of inter- and/or intra-muscular coordination that is present which may be more representative of sport specific tasks. However, a drawback of integrated measures of muscle strength is the inability to make specific inferences on individual muscles. This is because maximal strength during integrated tasks is a product of several muscles and joints working in coordination to achieve a single score, or simple successful or unsuccessful repetition. This is a limitation that isolated measures of muscle strength are able to overcome, where findings from the assessment can independently represent the action being assessed (i.e. hip extension).

2.4.4. Transfer of strength to physical performance

The transference of an exercise describes the degree of specificity that it has to a single sporting action, such as a sprint, jump or change of direction. Specificity will be discussed further in the following section, but generally it is common for practitioners to pursue exercises that demonstrate similar biomechanical, physiological or temporal facets to the performance marker one is attempting to improve. As such, it may also be useful for strength assessments to have a degree of transfer/association to a specific sporting action. This being due to the importance of maximal force production for explosive movements, as described in previous sections.

2.4.4.a, Specificity of movement

The topic of specificity is heavily debated within strength and conditioning research (Brearley & Bishop, 2019) with decades of research unfolding several layers of the ideology, from the four categories of periodisation (Bondarchuk, 1986) to the work from Siff and Verkhoshansky (1991) on the five laws of dynamic correspondence. More recently, Bosch (2016) has introduced a three-layer model based primarily on motor learning as a further dimension of specificity of training. Some of these concepts will be discussed in greater detail in the following sections. (2.4.4.b and 2.4.4.c)

Generally, specificity of exercise prescription can allow practitioners to break down the task outcome into parts, i.e. understanding specific joint kinematics or the rate of force development of a muscle group, in order to target and improve such factors in a similar environment to which their performed during the task outcome. An example of this would a drop jump exercise to improve maximum velocity running. The specificity of the drop jump to maximum velocity comes in the isolation and specific training of producing high force during short GCT. Therefore, improving this specific facet in isolation may hold increased transfer/crossover to the task outcome of maximum velocity running, where instances of high force during short GCT's occur (Haugen *et al.,* 2019).

In respect to the specificity of an assessment, it is important to consider that the specific facet of interest is already known, in this case maximum force. As previous sections described, the importance of maximum force production is well established, however factors surrounding orientation, magnitude and temporal elements of the assessment may be important to consider. Several theories have attempted to formalise the various ideas surrounding specificity in order to provide practitioners with a framework to plan training interventions from. The beliefs of the current research team are that these attempts are partly a somewhat overcomplication of biomechanics and generality vs specificity of movement. However, in an attempt to gain some clarity on these theories and relate them to strength assessment for hip extension, the remainder of this subsection will appraise these theories and provide practical examples specifically relating to hip extension.

2.4.4.b. Force vector theory

The force-vector theory attempts to quantify movement by its direction, often oriented either horizontally or vertically (Randell *et al.,* 2010; Zweifel *et al.,* 2017). This theory attempts to relate gym-based exercise to on field movements such as sprint-acceleration and vertical jumping by their direction relative to the global (world-fixed) coordinate system. Here, all movements in the forwards direction are deemed horizontal and all movements in the upwards direction are deemed vertical. In simple terms, any ground reaction forces perpendicular to the ground are defined vertical and any ground reaction forces parallel are defined horizontal.

Previously, the force-vector theory has been utilised largely in training intervention studies and studies associating exercises to athletic movement such as sprint-acceleration running. Many of these were described in the previous sections of this literature review. Generally, findings to date show that "horizontal force-vector exercises" such as the hip thrust (Contreras *et al.,* 2017; Abade *et al.,* 2019; González-Garcia *et al.,* 2019) or horizontal drop jump (Dello Iacono *et al.,* 2017; Gonzalo-Skok *et al.,* 2019) show better transfer to sprint-acceleration based actions, although some conflict is emerging (Jarvis *et al.,* 2019; Fitzpatrick *et al.,* 2019). In opposition, exercises with a "vertical force-vector" such as a back squat and various jumps have been better associated with vertically oriented movement such as vertical jump performance (Abade *et al.,* 2019; Dello Iacono *et al.,* 2017; Contreras *et al.,* 2017), vertical ground reaction force (Dello Iacono *et al.,* 2017) and maximum velocity (Loturco *et al.,* 2015; 2018). However, there is also a wealth of literature to explain improvements in acceleration from squat focused training interventions (Seitz *et al.,* 2014) as is introduced further into this text.

Upon interpreting the force-vector theory for assessment of lower limb strength representative of sprint-acceleration performance, it may be suggested that orientating the body to contract with a "horizontal force-vector" in an anteroposterior direction may be superior. However, the precise reasons for this may not actually be due to the "horizontal" nature of the movement. A shortcoming of the force-vector theory applied in this circumstance is the ill recognition of the athlete's orientation relative to the global coordinate system. For example, during acceleration the athlete leans forwards in order to project more force "horizontally" to displace the body in a forward's direction. However, relative to the local (athlete-fixed) coordinate system, the resultant direction of force is largely the same as the athlete's orientation (Fitzpatrick *et al.*, 2019). As such, Fitzpatrick *et al.* (2019) described the resultant direction of force relative to the athlete to be similar to that during a vertical jump, when working off the local coordinate system.

When applying to traditional strength exercises, the force-vector theory has further downfalls. The back squat has been described as a vertically dominant exercise as it holds an axial load with a vertical direction of force relative both the global and athlete fixed coordinate system. However, the hip thrust exercise has been deemed a horizontally dominant exercise due to it maintaining an anteroposterior load. The direction of force relative to the athlete fixed coordinate system is horizontal, yet the direction of force relative to the global coordinate system is vertical. Obvious differences arise between the squat and hip thrust due to the axial vs anteroposterior loading strategy that both exercises hold, respectively. Some of these include muscle dominance (Contreras *et al.* 2015; Delgado *et al.,* 2019; Neto *et al.,* 2020) and joint range of motion, albeit not yet evidenced in the literature (Contreras *et al.,* 2015). However, describing the squat as vertical and the hip thrust as horizontal generates confusion and may be mechanically incorrect.

For the reasons described above, it is of the research groups opinion that caution is to be taken when describing certain athletic movements as either horizontally or vertically dominant due to differences in athlete orientation during these actions. Furthermore, defining traditional strength-based exercises or assessments as horizontally or vertically dominant may also be unacceptable for similar reasons surrounding the local coordinate system of athletes when undertaking such exercise. Instead, it has been proposed that a greater understanding of biomechanics and dependence on another theory is built, the dynamic correspondence theory.

2.4.4.c. Dynamic correspondence theory

The dynamic correspondence theory seeks to outline a series of different facets that are hypothesised to be important to address when training for specific improvements in athletic performance (Suarez *et al.,* 2019). The five principles that underpin this theory are; the amplitude and direction of the movement, the accentuated region of force production, the dynamics of effort, the rate and time of maximum force production and the regime of muscular work. It has been suggested that each of these require consideration for proper application of the specificity principle and so will be examined below in respect to strength assessment tools for the motion of hip extension.

i. The amplitude and direction of the movement

Amplitude refers to the range of motion or degree of displacement that an exercise holds, and the direction outlines the path of the movement, similarly to the force vector theory. Regarding strength assessment, the amplitude facet will be dependent on whether the movement is dynamic or static and as such will influence its degree of specificity towards an athletic task, as was outlined in the previous section. Albeit a contentious topic (Fitzpatrick *et al.,* 2019), the direction of movement facet seems to have driven a considerable amount of research during both hip extension biased strength- (Contreras *et al.,* 2017; Abade *et al.,* 2019; González-García *et al.,* 2019; Fitzpatrick *et al.,* 2019; Jarvis *et al.,* 2019) and power- (Gonzalo-Skok *et al.,* 2019; Dello Iacono *et al.,* 2017) based exercise that are both for and against such theories. As was discussed in the force-vector sub-section to this chapter, labelling a movement as horizontal or vertical relative to the global coordinate system is described to be incorrect. Therefore, although the majority of research to date supports “horizontal” movements for hip extension dominance and transfer to on field performance, other mechanisms that explain their success must exist within these movements – some of which may exist within the remaining facets of this theory.

ii. Accentuated regions of force production

This facet refers to the effort of a particular muscle group during specific timepoints of a movement. For example, during athletic movements like maximal sprinting and acceleration the accentuated region of force production for the G_{max} during hip extension is during stance where the hip joint moves from flexed position to a position of hyperextension -20 deg (Orendurff *et al.,* 2018; Struzik *et al.,* 2016; Novacheck *et al.,* 1998). Preceding this, extension of the hip joint is achieved through acceleration from a flexed position during mid stance. Similarly, during a hip thrust exercise, G_{max} accentuation occurs at full extension (approx. 0 deg) and is reached from a flexed position with acceleration through a full range of motion to extension (Contreras, 2011). This largely occurs because of the anteroposterior loading strategy that a hip thrust holds. However, during a squatting task, the accentuated region for the G_{max} is in a position of deep hip flexion (90 deg +) and once full extension of the hip is reached, deceleration occurs in order to maintain a standing position (Contreras *et al.,* 2015). This largely occurs because of the axial loading strategy that a squat holds. Consequently, it may be suggested that a hip thrust, and anteroposterior loading strategy better represents sprint-acceleration performance when assessing hip extension capacity, for this specific facet.

iii. Dynamics of effort

The dynamics of effort facet refers to the force-velocity characteristics of a movement, albeit being a contentious topic which is to be shortly discussed in the subsection below. It is explained that training should encompass both high force magnitudes as well as fast contraction velocities that are exhibited in athletic movements. As such, a combination of high load – low velocity and high velocity – low load movement is proposed as the most effective regime (Suarez *et al.,* 2019). When referring to strength assessment, it seems as though this facet simply supports the requirement of maximal voluntary contraction to demonstrate an athlete’s capability under controlled conditions. However, whether this maximal contraction is to be collected under dynamic or static and integrated or isolated conditions is probably dependent on the objective of the task. Following this, it may be suggested that this is combined with a high velocity movement assessment. An example of this combination specific to hip extension would be a 1 repetition maximum hip thrust and a horizontal jump, both deemed hip extension dominant (Neto *et al.,* 2020; Contreras *et al.,* 2015 and Murtagh *et al.,* 2017; Nagano *et al.,* 2007, respectively).

iii.x. Force-velocity theory

The modernised force-velocity theory is based upon the original load-velocity theory outlined by A. V. Hill which attempted to explain the relationship between load and velocity within muscle. The original theory states that as the load imposed on muscle increases, the velocity by which the muscle can contract decreases. These theories have been confirmed by experimental studies that utilise isotonic quick release tasks on individual muscles with different isotonic loads to determine the velocity at which the muscle is able to shorten. The modernised force-velocity theory attempts to translate this theory to dynamic tasks (Jaric, 2015) such as sprint-acceleration (Samozino et al., 2016; Cross et al., 2017) and jumping (Samozino et al., 2008; 2010) tasks. Methods of calculating force-velocity relationships during these tasks have been introduced in recent years in order for practitioners to gain an insight into specific characteristics of their athletes (Jiminez-Reyes et al., 2017). However, Cleather et al. (2019) identified several inconsistencies surrounding impulse-momentum and work in the equations of the theory, such that incorrect assumptions of force being constant within movement are made, invalidating these equations. In addition, a fundamental flaw of the modernised force-velocity theory is the incorrect representation of the load-velocity relationship in isolated single muscle to complex dynamic whole-body tasks. For example, recent findings have expressed the poor generalisability of the force-velocity profile of isolated knee flexor and extensor strength to unilateral vertical jumping (Kozinc et al., 2020), Primarily, there is an incorrect association between load and force, two distinctly separate facets (Cleather et al., 2019). The modernised force-velocity theory states that as the velocity of movement increases, the amount of force that is exerted reduces. If this is the case, during maximum velocity sprinting the amount of force that is exerted to the floor should be minimal. However, we know that this is not the case (Brughelli et al., 2011; Nagahara et al., 2018). Instead, it should perhaps be stated that as load increases, greater forces must be exhibited in order to reach the same velocity. Considering the wealth of research within force-velocity profiling in the past, and its continued use in a range of settings (Mirkov et al., 2020; Simpson et al., 2020; Edwards et al., 2020; Junge et al., 2020), the authors herein advise readers to take caution when interpreting information within the area.

iv. Rate and timing of maximum force production

The rate and timing of maximum force production surrounds factors such as movement duration, GCT and rate of force development. This facets seeks to explain that sport-specific movement it often dependent on the ability to generate a lot of force in a certain time frame. This factor may not be so significant for strength assessment methods considering the intentions are generally maximum force irrespective of the duration. However, it has been suggested that static forms of strength assessment are superior when determining the rate at which maximum force is produced (Maffiuletti *et al.,* 2016). This is due to the confounding influence of joint angle and angular velocity changes that are held in dynamic tasks (Maffiuletti *et al.,* 2016). For this reason, isometric forms of strength assessment are preferred when determining the rate of force development of individual muscles or actions. This may be an important consideration for assessing hip extension, due to the short GCT's present during the stance phase of sprinting where the hip extensors are largely active, as indicated in previous sections.

v. Regime of muscular work

The final facet of the dynamic correspondence theory seeks to explain the transference of a movement by its type of muscle action, i.e. dynamic or static, as introduced in 2.4.2. In some cases, due to the cyclic action of many athletic movements it is believed that movements with a stretch shortening cycle are most closely related which hold a combination of eccentric and concentric contractions. Therefore, considering strength assessments it may be possible to believe that movement incorporating a stretch shortening cycle such as a 1 repetition maximum squat hold increased specificity to athletic movements when compared to a concentric only 1 repetition maximum deadlift or maximal voluntary isometric contraction. Having said this, the stretch shortening cycle exhibited in a 1 repetition maximum squat is considerably slower than during those found in actions such as jumping and especially those found in sprinting.

In addition, integrated strength assessment methods are unable to determine individual muscle maximal voluntary contraction capabilities in specific positions. To explain, isolated strength assessment forms for the hip extensors have the capacity to determine the angle at which an individual muscle can produce peak torque or force, depending on whether the action is dynamic or static. Therefore, the notion of angle specificity becomes favourable for these forms when comparing to athletic movements such as the late swing phase of gait, when attempting to determine the capacity of a muscle at a specific length or in a certain position. Depending on whether the muscle undergoes an eccentric or isometric action during late swing (Van Hooren & Bosch, 2016), either dynamic or isometric strength assessment forms may be better representative if specificity towards hamstring strain injury during sprinting is the objective.

In summary, the dynamic correspondence theory suitably directs practitioners to question the aims and objectives of data collection with strength assessments. In addition, several facets from this theory may be used to rationalise the choice of assessment tool and refine selections to ensure that worthwhile and useful data is being collected. When looking at hip extension specifically, the debate of generality vs. specificity stands and is an important consideration to be mindful of in future research looking into the topic.

2.4.5. Bilateral and unilateral assessment of strength

On the topic of training and assessment specificity, it seems suitable to introduce the notion of bilateral vs. unilateral training and assessment. It is widely understood that most propulsive actions that occur within competitive field-based sport are generated in a unilateral rather than bilateral fashion, such as accelerating, sprinting, changing direction and jumping. As such, it can be said that maximum force is rarely exerted bilaterally in the same muscle group during athletic performance. One exception of this statement is a bilateral jump, yet these occasions are much less frequent than horizontal explosive actions (Murtagh *et al.*, 2019). Considering the above, assessing the force generating capacity of a muscle unilaterally may hold greater specificity and better replicate on-field athletic capacities. Nonetheless, one opposing fact to be mindful of is the less stable conditions that often accompany unilateral assessment for maximum force, thereby lowering the relative magnitude of force expression in comparison to bilateral assessment. Further information on such factors are to be discussed in future chapters.

Aside specificity, understanding sporting asymmetry with unilateral assessment is often used to describe interlimb differences in parameters such as force output or muscle size.

The presence of these asymmetries is likely to arise as a function of limb dominance which is often augmented by long-standing participation in sport. Such instances of asymmetry have been highlighted in a review paper across several sporting disciplines (Maloney, 2018).

Asymmetry that may exist between limbs when screening could be important to understand for performance and injury related purposes (Bishop *et al.,* 2017; Maloney, 2018). Furthermore, monitoring the degree of asymmetry may be important during return to play from injury to one specific leg. As with the information presented earlier in the chapter, it is generally recommended that restoring interlimb asymmetry levels in the hamstring is advised, and a commonly adopted threshold is >10% (Buckthorpe *et al.,* 2019). Having said this, a recent systematic review and meta-analysis presented a list of forty-nine risk factors for subsequent HSI, yet interlimb asymmetry was not one (Green *et al.,* 2020). When observing performance during running based tasks, factors surrounding sprint performance such as horizontal force (Brughelli *et al.,* 2010; Lord *et al.,* 2019) have been found to be reduced after HSI. Furthermore, peak torque (Lord *et al.,* 2017) and EMG excitation (Timmins *et al.,* 2014) of the hamstrings is reduced to a greater level after repeated sprinting in a previously injured hamstring muscle. Although it cannot be confirmed whether these decrements are a cause or result of the hamstring strain, it is generally accepted that restoration of an injured tissues function to a pre-injured level is required. Therefore, regular assessment of unilateral function is required in order to provide these markers.

From a performance standpoint, to date evidence on the influence of interlimb asymmetry is conflicted and neither confirms nor denies a positive or negative influence (Maloney, 2018). However, research surrounding maximum force asymmetries in the muscles required to extend the hip is relatively absent. Having said this, a single case study investigating the suitability of targeted hip extensor strength training to reduce horizontal force asymmetries during sprinting exhibited favourable findings (Brown *et al.,* 2017). The researchers interpreted their findings to suggest that a period of targeted hip extension training to reduce asymmetry during sprinting may have decreased injury risk whilst improving sprint performance. Theoretically, this concept can be applied to asymmetry in a maximum force assessment of the hip extensors. Here, such asymmetry may help explain inconsistent or unbalanced force expression during propulsive actions such as maximal acceleration. These instances may hold important ramifications for suboptimal generation of ground reaction force during acceleration on the weaker limb leading, to a shorter projection of the athletes COM. In addition, excessive overreliance of either the contralateral limb or another muscle group may occur to make up for the unilateral hip extensor deficiency and lead to injury. To date, the research team are unaware of any research to investigate such theories for maximum force expression of the hip extensor muscles.

To summarise, although somewhat inconclusive, it seems as though the presence of interlimb asymmetry may have important implications for the subsequent behaviour of muscles during athletic tasks. With the hip extensor muscles being a significant contributor to force generation during such tasks and considering propulsion of the body's COM is often exerted unilateral, it seems as though an assessment of unilateral force is warranted. Such information is to be readdressed further into the text.

2.4.6. Environmental constraints of soccer

Prior to selecting a battery of assessment tools for a given athlete or group of athletes, an understanding of the environment for which they are going to be used within is required. In the case of professional soccer, the environment is largely represented by periods of competitive fixture congestion and numerous technical and tactical training sessions. As such, availability of time for sports science and medicine departments to carry out their work is limited and when available, this time is generally occupied by recovery strategies to increase athlete availability for training and matches. As a result, the collection of strength assessment data with these athletes may be seen as a physiological burden and too time consuming.

Dynamic assessment methods such as isokinetic dynamometry may not be suitable as they have the capacity to elicit increased physiological stress to the targeted muscle or joint action, as described in previous sections (2.4.3.a.i).. Furthermore, dynamic assessment with isokinetic dynamometry is often time consuming to setup, requires a degree of familiarisation for the athlete and assessor and access to the equipment can be expensive. Such undesirable factors may not be so present in one repetition maximum type dynamic measures, especially in trained athletes, although information on the topic area is poorly studied (Arazi & Asadi, 2013). Having said this, the frequency of traditional maximal strength training in professional soccer is often limited and largely dependent on cultural philosophies present within organisations. As such, an athlete's lack of exposure to such methods of training may lead them to be inappropriately trained to complete such assessment batteries and at an increased risk to sustain injury (Buckner *et al.,* 2017). Static forms of strength assessment may prove a suitable alternative due to the reduced physiological load that is applied to a muscle or joint action during isometric contraction (Allen *et al.*, 1985). Examples of such strength assessment tools that have become popular in recent years are the NordBord and ForceFrame (VALD Performance Pty Ltd, Newstead, Australia) and KangaTech (KangaTech Pty Ltd, North Melbourne, Victoria) perhaps due to their simplicity of use and ease of collecting data for large cohorts of athlete in a short period of time. Albeit popular assessment tools, information surrounding validity and reliability of some of these tools under isometric conditions are somewhat limited and/or inconclusive (table 2.1)

Furthermore, the associated metrics and training methods that accompany present strength assessment devices, such as eccentric knee flexor strength, have both favourable (Ishøi *et al.,* 2017; Krommes *et al.*, 2017) and less-favourable (Mendiguchia *et al.,* 2020; Suarez-Arrones *et al.,* 2019; Freeman *et al.,* 2019) effects on physical performance in previous investigations. However, literature surrounding the use of the associated isometric variables is yet to be seen. In summary, the above is a reminder that assessment tools alone may not necessarily provide answers to much more complex facets like physical performance and injury susceptibility.

Table 2.1. Reliability and validity literature for popular strength assessment tools in elite sport.

Equipment Type	Reliability	Validity
NordBord (isometric knee flexion)	No studies	No studies
ForceFrame (isometric ab/adduction)	No studies	O'Brien *et al.* (2019) r = 0.53-0.71 (moderate to good)
KangaTech (isometric knee flexion)	Ransom *et al.* (2020) ICC – 0.83-0.97 (high to very-high)	No studies

2.4.7. Rationale for the development of a new tool to assess isometric hip extension strength

Information from section 2.4 has presented several fundamental considerations that are faced when determining the type of assessment tool for use. Primarily, test validity and reliability is essential for practitioners to have confidence in their assessment tools representing what they claim to be. It is then important to determine what the assessment will be used for, what information required and how it will inform future practice. Here, the choice of dynamic or static and integrated or isolated forms of strength assessment are to be decided on (2.4.3) and the degree of generality or specificity of the assessment tool is to be considered (2.4.4). Within this decision-making process, environmental constraints may limit and guide the direction of choice where traditional measures may be deemed inappropriate for use. This can be due to factors surrounding the inducement of increased physiological stress, time consuming protocols and infrequent exposures to the required exercise techniques (2.4.5). During these circumstances, a simple static and isolated isometric test may be considered due to its ease of use, fast procedures and possibly safer modality of MVC collection.

Considering this, it is the research groups opinion that future investigations into hip extension for HIE performance and injury management may wish to utilise measures that are both static (isometric) and isolated in nature. This may especially be the case when being utilised within time constrained environments and surroundings where more dynamic and integrated forms of strength assessment are less accepted. An isolated measure also has the advantage of representing an individual joint or muscle action which may be useful when measuring hip extension strength and linking findings to physical performance and injury susceptibility. Once a decision has been made on these fundamental considerations for strength assessments, careful notice is to be taken to several more precise considerations that are to be addressed in the succeeding text within chapter 3. These considerations may be utilised in accordance with the information from 2.4.4 to determine the specificity of the assessment and future relatedness to performance.

2.5. Conclusion

The primary objective of chapter 2 was to critically evaluate the role of hip extension for injury management and physical performance improvements, two key constructs of success in soccer. A secondary objective of chapter 2 was to understand the importance of strength in soccer and the difficulties surrounding the assessment of such aptitudes. A final objective was to understand the fundamental requirements and considerations of strength assessment when determining the suitability of a tool for use in future investigations. It seems as though there is substantial evidence to underpin the importance of hip extension for injury management and physical performance. It also appears that the availability of a suitable and field-friendly strength assessment tool for hip extension is absent. As such, it is of the research groups interest to make further exploration into the assessment of isolated and isometric hip extension strength and the development of a new assessment tool. Successful development may then be used to drive future research within the injury management and physical performance specific to hip extension.

Chapter 3

The development of a novel isometric hip extension strength assessment tool.

3.0. Interlude

Chapter 2 confirmed the requirement of assessment tools for understanding performance capacity and injury susceptibility. The complex nature of developing valid and reliable assessment tools was presented and it was indicated that several considerations require attention when designing and utilising such tools. Currently several assessment methods for hip extension strength are available yet few exist as suitable for use in applied professional soccer. An understanding of the environment and purpose for which an assessment tool is to be used were outlined as important factors that may influence decision making processes. Two of these decisions are the type of muscle contraction that is to be assessed and the tool that is to be selected to assess it. These decisions contribute to a framework of key considerations surrounding the successful development of an assessment tool, of which all are to be addressed in the coming chapter.

The following chapter introduces a group of key considerations that are to be addressed upon developing strength assessment tools (3.1.). These considerations are then implemented throughout a process of tool development for a novel assessment of isometric hip extension strength (3.2.). Throughout this section, key intervals during the timeline of development are highlighted during which the considerations presented in 3.1. have been addressed. Finally, the hip extension bench (HEB) is presented with information surrounding setup, utilisation, practical application and future directions for use (3.3.)

3.1. Framework of considerations for successful assessment tools

Chapter 2 introduced a series of fundamental considerations that practitioners must prioritise before the introducing a strength assessment tool to their environment. The decision-making process will primarily be influenced by the constraints of the workplace, the specific the needs of the practitioner and the purpose of the assessment. Following this, chapter 3 seeks to reiterate these considerations and introduce a series of secondary considerations required to refine tools specifically for hip extension. These considerations are also believed to be essential in order for a strength assessment tool to hold suitable validity and reliability during data collection and interpretation and are presented in table 3.2

3.1.1. Contraction type

As was indicated within chapter 2, the type of strength assessment plays a fundamental role in muscle function. *Dynamic* and *static* assessments of strength generally represent detached physical capacities yet may be somewhat related, and both hold their advantages and drawbacks. *Integrated* assessments seek to understand gross-movement analysis whereas *isolated* assessment is able to separate muscle specific function. As was concluded at the end of chapter 2, the present research seeks to investigate hip extension in an isolated and static form. As such, the below text discusses the successes and failures of present measures of hip extension strength relating a muscle-specific isometric testing conditions.

Limitations of current measures of hip extension strength. During a pushing hip extension task under "isometric" conditions, it can be difficult to eliminate the possibility of athletes employing a slight countermovement and/or concentric action of the muscles prior to isometric contact with the dynamometer. Such occasions may be particularly common where handheld dynamometry is used against an assessor's manual resistance (Lue *et al.,* 2009; Thorborg *et al.,* 2013*;* Wilkholm *et al.,* 1991). In these situations, the isometric nature of the contraction will be false and leave practitioners unable to make correct interpretations from the data. Allowing athletes to have room for movement within an assessment setup allows for possibility of these countermovement and/or concentric actions as may be found in previous research during the prone position (Scott *et al.*, 2004; Nadler *et al.,* 2000) or standing where trunk flexion may promote a countermovement (Kollock *et al.,* 2010). It has to be assumed that trials of any non-isometric conditions would be removed, and instructions would be given to repeat the trial, yet this is just an assumption. By utilising well oriented and correctly fixed equipment setups and providing athletes with robust instructions, controlling the type of contraction may become easier and more consistent.

3.1.2. Equipment type

Within chapter 2, the necessity of maintaining valid and reliable strength assessment tools was highlighted. However, issues surrounding environmental constraints to tool implementation was also given. Therefore, it may be suggested that an optimal hip extension strength assessment tool successfully adheres to both considerations and may be largely governed by the type of equipment that is used. Kollock *et al.* (2008) introduced a three-stage measurement complexity categorisation model for strength assessments of the hip joint. Within this model, the "tertiary" measure is generally the validated gold-standard and represents isokinetic dynamometry, suggested to be the most complex. This being considered, secondary measures are popular within the applied field and include handheld dynamometers and portable fixed dynamometers.

With that being said, it may also be deemed unsuitable to incorporate handheld dynamometry into an assessment battery for groups of athletes due to the limited sensitivity that handheld dynamometers may hold. Portable fixed dynamometers are an alternative equipment type and seem to represent the compromise between handheld dynamometry and isokinetic dynamometry. These measures of hip extension strength do not come without limitations, to be addressed in the next paragraph, and are also limited for use within the applied field due to their inaccessibility, high expense, complexity and impracticality for use when testing a large number of athletes (Paul & Nassis, 2015; Chamorro *et al.*, 2017; Ekegren *et al.*, 2009; Kollock *et al.*, 2013; McCall *et al.*, 2015). Secondary measures of hip extension strength include portable fixed dynamometers and handheld dynamometry (Lue *et al.*, 2009; Nadler *et al.*, 2000; Scott *et al.*, 2004; Seko *et al.*, 2015; Thorborg *et al.*, 2013; Kollock *et al.*, 2010) and are popular for their simplicity and portability. Regarding primary methods of strength testing, popularity occurred in previous years when objective measures were unattainable. Subjective 5-point scales have been used by practitioners, yet obvious limitations exist regarding the lack of objectivity and inability to detect small changes in strength (Scott *et al.*, 2004). Such limitations have led to questions towards the value of such measures (Cuthbert & Goodheart, 2007) so are often rendered largely inadequate in the modern day.

Limitations of current measures of hip extension strength. Looking into the currently available assessments of isometric hip extension strength, tertiary measures fit the time-consuming and clinical infeasibility drawbacks that come with these kind of measures. Such setups require the utilisation of leg braces (Meyer *et al.*, 2013) and several straps (Meyer *et al.*, 2013; Julia *et al.*, 2010) in order to avoid issues surrounding joint stabilisation, a consideration discussed later in this text. Nadler *et al.* (2000) described handheld dynamometry to be a more practical alternative to isokinetic dynamometers due to shorter setup times, increased portability and reduced expense. As such, Keep *et al.* (2016) investigated the concurrent validity of handheld dynamometry, yet only found correlations to be moderate. This could be explained by the various limitations surrounding handheld dynamometry, such as insufficient tester strength and inconsistent dynamometer positioning (Wikholm *et al.,* 1991; Thorborg *et al.,* 2013). External fixation utilising portable fixed dynamometry can be a useful solution as long as it is quick and applicable in busy environments (Thorborg *et al.,* 2013). Portable fixed dynamometry has seen some positive findings (Kollock *et al.,* 2010; Nadler *et al.,* 2000; Scott *et al.,* 2004), however the additional use of extra strappings or fixations again increases time-cost and reduces clinical feasibility. Further limitations to these assessment techniques also exist and will be discussed further into the text. Therefore, it seems as though there is a clinical feasibility and tool validity crossover that is currently proving an issue for assessment tools.

As a subsection to this considerations, it may also be important to note that calibration of dynamometers should occasionally be revisited. Dynamometer calibration can be altered over time due to various instances surrounding general "wear-and-tear" of the equipment and can be especially common where frequent utilisation of equipment occurs. Insufficient unit calibration may present as a threat to both the validity and reliability of measures that are collected. Therefore, it is advisable to service dynamometers with frequent recalibration before and after periods of heavy usage, or at least or on a season to season basis.

3.1.3. Limb and joint positioning

Altering the position and angle of a joint for which it must produce force from can have a significant effect on the functioning muscles of the given action of interest. Assessing the strength capacity of a muscle across various positions will alter the position at which accentuated force is produced. This can of course have implications for assessment outcomes or transference of training to performance, whereby maximal contractions at specific angles may have better carryover to athletic movements, as detailed in 2.4.3.b in chapter 2 (Suarez *et al.,* 2019). Changes in joint angle are found to influence muscle function by altering its moment arm, normalised fibre length, regional muscle size, muscle and tendon stiffness and neural drive. When looking specifically at moment arms, the force producing capacity of larger muscles such as the G_{max} are usually influenced more by a change in joint angle (Vigotsky *et al.,* 2015), as torque = force x moment arm length. Investigating neural drive in response to joint angle changes via sEMG may also provide useful information, however careful consideration must be taken during equipment setup and data acquisition and handling (Hermens *et al.,* 2000; Halaki & Ginn, 2012). Otherwise several limitations of sEMG surrounding noise interference from inconsistent surface electrode placement and insufficient prepared skin may provide inconsistency in results. Several investigations have been made exploring the influence of joint angle on muscle function to outline the importance of standardising procedures of data collection. Each of these specific to hip extension are described below.

As the muscles of the hip extensors originate and insert at different positions, they contribute to different actions and torques against the femur and pelvis. Alongside hip extension, the G_{max} contributes to external rotation and abduction (McAndrew *et al.,* 2006). The crossing of the hamstring muscles about the hip and knee joint renders them biarticular muscles resulting in both extension of the hip and flexion of the knee. Finally, the Add_{mag} muscles origin and insertion renders it a hip adductor alongside its capacity to extend the hip (figure 3.1 and table 3.1). As such, the muscle specific contribution to movement about the hip is complex and will strongly depend on body segment positioning. This may partly explain the great conflict seen within the literature regarding changes in force, torque and activation across various hip and knee angles during hip extension, as discussed by Bazett-Jones *et al.* (2017). Analysis of these actions have been made through estimates via modelling techniques (Sherman *et al.,* 2015) or indirectly through measures of muscle torque and activity via force gauges and electromyography as will be outlined below.

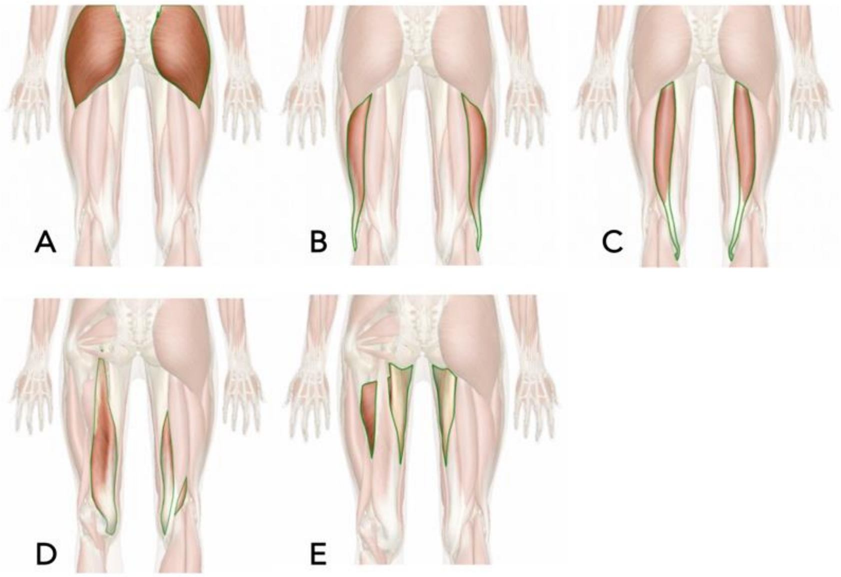

Figure 3.1. The major hip extensors muscles; A – gluteus maximus, B – biceps femoris long head, C – semitendinosus, D – semimembranosus, E adductor magnus

Table 3.1. Origin and insertion information for each major hip extensor muscle.

Muscle	**Origin**	**Insertion**
Gluteus maximus	The external surface of the ilium, the fascia of the erector spinae, the dorsal surface of the sacrum, the lateral margin of the coccyx and the sacrotuberal ligament	Upper fibres insertion point is at the posterior part of the iliotibial tract and the fascia latae muscle. Lower fibres insert at the gluteal tuberosity of the proximal femur.
Biceps femoris long head	The ischial tuberosity and the sacrotuberous ligament	The head of the fibula and lateral condyle of the tibia
Semitendinosus	Upper inner quadrant of the posterior surface of the ischial tuberosity	Upper part of the medial surface of the tibia
Semimembranosus	The outer surface of the ischial tuberosity	The medial tibial condyle, the oblique popliteal ligament and the popliteal fascia

Hip flexion/extension. Increasing hip flexion is found to reduce the G_{max} moment arm from 78 – 32 mm, peak at 35 – 40° and shorten either side for the grouped hamstrings (75 mm) and increase to a plateau at 70 – 75° for the Add_{mag} (57 mm), evidenced by computed tomography (Németh & Ohlsen, 1985). Such findings are confirmed in Ward *et al.* (2010)'s comprehensive clinical commentary. In addition, increasing hip flexion angle between -20 and 60° is seen to increase the moment arm of the BF_{lh} until plateau (Visser *et al.,* 1990). When considering force/torque production, isometric hip extension elicits greatest torque at 90° hip flexion when compared to 60°, 30° and 0° (Worrell *et al.,* 2001; Bazett-Jones *et al.,* 2017, 30° and 0° only). Regarding muscle activity, a decrease and no-change of G_{max} and grouped hamstrings electrical activity is found when increasing hip flexion, respectively (Worrel *et al.,* 2001). As such, it has been hypothesized that the increase in force/torque at angles of greater hip flexion is likely due to an increased moment arm of the grouped hamstrings (Németh & Ohlsen, 1985; Dostal *et al.,* 1986; Neumann, 2010) and adductor muscles (Neumann, 2010) and/or that the G_{max} and/or hamstrings are at a more optimal length-tension relationship (Bazett-Jones *et al.,* 2017).

Hip internal/external rotation and abduction/adduction. Abducting and externally rotating the hip reduces the distance between origin and insertion points of the G_{max} and thereby shortens the muscles length. During isometric hip extension assessment G_{max} EMG amplitude is augmented in positions of hip abduction (Suehiro *et al*., 2014; Kang *et al*., 2013) and external rotation (Sakamoto *et al*., 2009). Similar findings of increased G_{max} sEMG activity can also be seen during a dynamic hip thrust exercise where an increased distance between the feet elicit higher G_{max} activation (Collazo Garcia *et al.,* 2018). Upon combining both abduction and external rotation, G_{max} activity is rendered even higher (Suehiro *et al*., 2014), which may or may not have implication for the force generating capacity of the muscle. Regarding grouped hamstring EMG, positions of abduction (Kang *et al*., 2013) and/or external rotation (Sakamoto *et al*., 2009) present opposing behaviour to the G_{max} where a reduction in activity is found. Information surrounding the behaviour of the Add_{mag} during these instances is sparse, yet it may be reasonable to assume that the muscle would be lengthened.

Pelvic tilt and trunk stabilisation. Within the injury section of chapter 2, the relationship between hip extension and trunk control was evidenced as an important consideration for the prevention of hamstring strains. Therefore, it may come as a surprise that literature surrounding trunk control during hip extension assessment is limited. With that being said, some work has been undertaken in dynamic exercises (Queiroz *et al.,* 2010; Kim & Seo, 2015; Tateuchi *et al.,* 2012; Choi *et al.,* 2015). Performing a "knee stretch" exercise on a reformer exercise machine (Queiroz *et al.,* 2010) or quiet standing during whole body vibration (Kim & Seo, 2015) whilst in posterior pelvic tilt significantly increases sEMG activity of the G_{max} musculature. This can be explained by the force-coupling of the G_{max} and abdominal muscles to selectively tilt the pelvis posteriorly (Kim & Seo, 2015). In practice, resistance bands have been utilised to promote hip abduction, increase G_{max} activation and in turn promote posterior pelvic tilt during bridging exercise (Choi *et al.,* 2015). It is also noteworthy that abdominal activity can influence pelvic stability and thereby influence G_{max} activation, as found during abdominal drawing-in manoeuvre during prone hip extension (Oh *et al.,* 2007; Kim *et al.,* 2014). Finally, runners who display a reduced hip extension range are also seen to display higher levels of anterior pelvic tilt (Schache *et al.,* 2000). Therefore, it may be of interest for future work to establish means of eradicating reduced range through assessment and training of the hip extensor muscles.

Knee flexion/extension. As a final consideration of joint behaviour, knee flexion/extension is generally only associated with a change in hamstring activity, due to the G_{max} and Add_{mag} not crossing the knee joint. As knee flexion angle increases (0, 30, 60, 90, 110°), G_{max}, BF_{lh} and ST activity follows a general increase, decrease and decrease respectively (Kwon *et al.,* 2013), with the G_{max} and BF_{lh} being significance lower at angles of 0 - 15° and 60° and above, respectively. These findings are in agreement with Sakamoto *et al.* (2009) who investigated both the G_{max} and ST between angles of 0° and 90°. It seems that excessive knee flexion causes an active insufficiency of the hamstrings muscles when acting as hip extensors. It could be that this is due to a reduced active and/or passive length-tension relationship and suboptimal cross bridges with fewer actin and myosin overlap. This in turn has been shown to reduce the extensional torque about the hip (Kwon *et al.,* 2013) and may explain the increased requirement of the G_{max} musculature. Therefore, it seems advisable that when looking to isolate the G_{max} during assessment or training that the knee if considerable flexed.

Limitations of current measures of hip extension strength. In current measures of hip extension, the rigorous factors related to consideration of limb and joint positioning may explain previous findings often display suboptimal reliability coefficients and come with several limitations. A common limitation discussed within the literature is the inability to control trunk stability during hip extension assessment (Lue *et al.,* 2009; Meyer *et al.,* 2013; Julia *et al.,* 2010; Keep *et al.,* 2016), although these limitations are not presented even if they still may be present (Scott *et al.,* 2004; Nadler *et al.,* 2000; Kollock *et al.,* 2010). Such instances are most certainly linked to the fact that the assessments were completed with an open-kinetic chain (OKC) which does not lend itself to stabilising joints (as explained below), even when straps are used in an attempt to limit the instability, as discussed previously (Meyer *et al.,* 2013; Julia *et al.*, 2010; Keep *et al.,* 2016). Such instances can of course influence both activation of the G_{max} and hamstrings and the contribution of other trunk extensors towards the force output. Another common methodological limitation found is the lack of or poor standardisation of hip and/or knee angles during assessment. Often, knee angles are approximated (Scott *et al.,* 2004; Nadler *et al.,* 2000) or simply asked to manually maintain an extended position (Julia *et al.,* 2010) and only on one occasion was it specifically isolated in one position with a brace (Meyer *et al.,* 2013). The influence inconsistent joint angles may have on force production is evident from the abovementioned literature. Assessments in the prone position also generally estimate the level of hip extension upon contact with the dynamometer (Scott *et al.*, 2004; Nadler *et al.*, 2000) rendering cross-comparison of participants impossible. Finally, the OKC nature of most current assessment methods leaves the working limb free to adduct, abduct and trunk to become relatively unstable, especially when in a standing (Kollock *et al.,* 2010) or prone-standing position (Lue *et al.*, 2009; Keep *et al.,* 2016).

It seems as though concise methods of standardising and fixing limb and joint position have proved difficult in the past. Considering the great influence changing joint angle can have on the force generating capacity of a muscle or group of muscles, it seems vital that strict methods are revisited, and standards are proposed upon the development of a novel tool.

3.1.4. Open vs. closed chain

Open kinetic chain movement occurs where the most distal segment from the body is free and not fixed to an object, such as a hip extension cable kick back. These conditions could render assessments as difficult due to the insufficient stability demands that can be present, especially during hip extension assessment. With the distal segment of the lower limb free during hip extension, it is difficult to control joint motion in various planes such as knee flexion, hip internal/external rotation and ab/adduction. Such instances may result in uncertainty in considerations surrounding joint angle as discussed above and as such influence the contribution of each muscle towards the resultant force. Alternatively, closed kinetic chain (CKC) exercises require the distal segment to be fixed, such as a barbell hip thrust. Movement in CKC exercises are generally seen to hold increased stability and as such may allow athletes to produce greater force than during OKC movement. Increasing stability at the distal end through closed-chain exercise is also seen to improve G_{max} muscle activity during hip extension exercise (Madacam & Fesir, 2019).

Aside the stability demands of OKC movement, it has also been suggested that CKC movement has better transference to athletic performance (Suarez *et al.,* 2019). Considering the fact that almost all movement requires consistent GRF it seems suitable to suggest that when assessing the force generating capacity of muscles that consistent GRF is also present. These suggestions have been confirmed in the past where better associations between CKC exercise have been found with performance of athletic movements (Blackburn & Morrissey, 1998; Augustsson *et al.,* 2000).

Limitations of current measures of hip extension strength. To the authors knowledge, all currently available measures of isometric hip extension strength are performed in an OKC movement. In a prone position, the lack of fixing at the distal end of the limb leaves motion such as hip internal/external rotation to become hard to control. This may be further increased during assessment where knee angle is not fixed, potentially allowing for the hamstring to freely change muscle-length prior to and during assessment (Worrell *et al.,* 2011; Scott *et al.,* 2004, Nadler *et al.,* 2000). Similar issues may also arise in a standing position where unwanted ab/adduction, int/external rotation and trunk flexion/extension may occur during the "kick-back" motion (Kollock *et al.* 2010). Therefore, a common limitation of the movement in an OKC is the influence it may have on changing limb and joint positioning, such as muscle length, joint angles and moment arms.

3.1.5. Direction and transference of movement

The importance of horizontal force and power production for performance of HIE's and sprint-acceleration was confirmed in chapter 2. Furthermore, research surrounding the transference of training exercises was also introduced as a means of hypothesising similar mechanisms for assessments of strength. Although authors have criticised the use of the force-vector theory (Fitzpatrick *et al.,* 2019), it is commonly believed that there is a directional specificity of transfer of exercises to performance of athletic movements (Randell *et al.,* 2010*;* Macadam & Feser, 2019), albeit perhaps not because of the direction of force relative to the global-fixed coordinate system. For example, exercises that are deemed to hold a "horizontal force bias" are consistently suggested to be preferential to develop movement that is deemed "horizontally biased" such as sprint-acceleration (Contreras *et al.,* 2011, 2016, 2017; Loturco *et al.,* 2015; 2018; Zweifel *et al.,* 2017; Abade *et al.,* 2019; González-Garcia *et al.,* 2019; Gonzalo-Skok *et al.,* 2019; Dello Lacono *et al.,* 2017). Because of this, it could be suggested that strength assessments should also incorporate similar facets to enable a greater representation of force that is produced during athletic movement.

Exercise variations such as the barbell hip thrust have become a popular exercise which require a maximal voluntary contraction of the lower limbs in an anteroposterior direction (Contreras *et al.,* 2011) and have been implemented on several occasions in an attempt to improve athletic performance in sport (Neto *et al.,* 2019). Aside the theories surrounding force-vectors, the hip thrust exercise is also in agreement with several facets surrounding dynamic correspondence (Suarez *et al.,* 2019). These include the CKC nature of the hip thrust, similar accentuated region of force to sprint-acceleration performance and combination of high-load low-velocity or low-load high-velocity dynamics of effort that are achievable with the exercise. Although there is very limited research surrounding direction of force, anteroposterior (front to back) loading may also transfer better to athletic performance than posteroanterior (back to front) loading. A simple reason for this is that during horizontally biased athletic movements such as acceleration and sprinting, athletes must initially overcome horizontal braking forces that are applied to the body in an anteroposterior direction. The force vector hypothesis would approve this theory, because when standing the horizontal force vectors are anteroposterior (Contreras *et al.,* 2016). This is particularly relevant to sprinting due to the conclusions made in chapter 2 that horizontal force, velocity and impulse have strong associations with sprint running.

Limitations of current measures of hip extension strength. The majority of current hip extension strength assessments utilise a prone or standing position where a dynamometer is placed posterior to the human body (see figure 3.2 for examples). In these positions, force application is being applied against resistance in the posteroanterior direction. Due to the reasons described above surrounding the anteroposterior direction of force whilst running, it may be reasonable suggest that a superior measure would provide resistance anterior to the human body during strength assessment. Additionally, it seems that several other facets of the force-vector and dynamic correspondence theories are not met in current measures of hip extension strength which may deem them non-representative of hip extension capacity during athletic movement. Therefore, when looking specifically at an assessment of maximal hip extension strength, a setup with similarities to the hip thrust could overcome current assessment downfalls and prove to hold successful representation of hip extension force application in athletic movements.

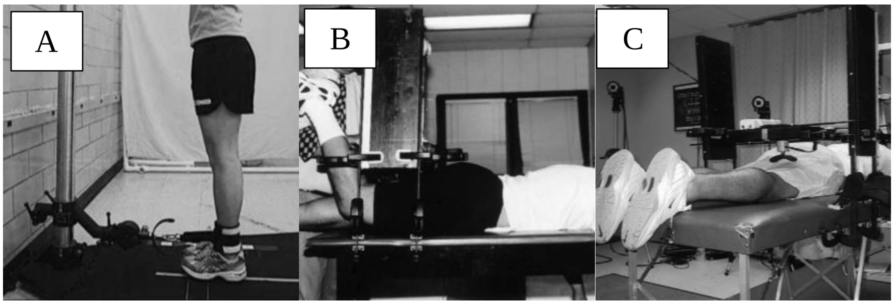

Figure 3.2. Current strength assessment measures for hip extension utilising a posterior to anterior direction of force application (A = Kollock *et al.*, 2010, B = Nadler *et al.*, 2000, C = Scott *et al.*, 2004).

3.1.6. Location for acquisition of force

In order to assess the force generating capacity of single joints it is important to consider the position at which force is being measured. Without this, small changes in dynamometer position may alter the equipment moment arm and thus ability for the athlete to produce force (Tsaopoulos *et al.*, 2011). In order to isolate the hip extensors during assessment, it is important that the point of contact for force acquisition is proximal to the posterior surface of the knee joint. Such a position will ensure that a flexion torque about the knee joint is eradicated. This has been discussed previously after finding reduced reliability (Kollock *et al.,* 2010) and validity coefficients (Kollock *et al.,* 2013) for hip extension in comparison to other assessments of hip strength in other planes. Here the position of force acquisition was on the posterior surface of the lower leg, proximal to the medial malleolus via an ankle strap. Thorborg *et al.* (2013) used a similar position of force application yet in a prone position which was correctly deemed a measure of hip extension and knee flexion. The above setups may have allowed for knee flexion torque to contribute to the assessment, which may provide invalid measures of an athlete's hip extensor strength. For instance, an overestimate of athlete strength may lead to incorrect evaluation when making assumptions from data that is collected.

It may also be important to consider the difference between anterior and posterior positioning of acquiring force for reasons aside those described in the previous consideration. Generally, the collection of hip extension force data has been acquired with the participant "kicking back" onto a dynamometer that is posteroanterior to the body where contact with the lower hamstring area is made (Lue *et al.,* 2009; Meyer *et al.,* 2013; Julia *et al.,* 2010; Keep *et al.,* 2016; Scott *et al.,* 2004; Nadler *et al.,* 2000; Kollock *et al.,* 2010). During this type of assessment, as alluded to previously, it seems that difficulty comes in controlling trunk motion. This commonly causes an anteriorly tilted pelvis and subsequent contribution of force from additional muscles such as the spinal erectors. Again, such instances may render data uninterpretable. Therefore, collecting hip extension force from the anteroposterior side may provide a solution where the athlete is required to push against a dynamometer at the iliac crest region or hip crease of the anterior hip. Generating force in the anteroposterior direction allows participants to maintain a fixed pelvic position by "locking it in" against an immoveable surface and subsequently reduce the variation in trunk motion that is present within current assessment methods. To the researcher's knowledge, such methods of assessing hip extension are yet to be investigated but are commonly utilised in gym-based exercises such as the barbell hip thrust (Contreras *et al.,* 2011).

After investigation, it seems as though several factors are required to be considered upon the development of a novel assessment or training tool (table 3.2). Upon overlooking or disregarding any of the abovementioned considerations, the validity and reliability of such tools may be under threat. Such instances may increase the error that a tool is accompanied by and may lead to subsequent misinterpreted data and ill-informed decisions. Therefore, close attention should be given to each consideration during the development of a novel tool to assess and train isometric hip extension strength. The remainder of this section seeks to provide a timeline-structured outline of the development of the Hip Extensor Bench (HEB), a novel assessment tool to assess isometric hip extension strength. Throughout the text, reference will be made to the most relevant considerations discussed above, where they either have or haven't been successfully met. For example, the selection of a supine position in all 3 phases of the assessment tool development in order to conform to several of the considerations outlined above. In addition, the selection of a supine glute bridge / hip thrust reminiscent position was also made due to the wealth of research surrounding superior hip extensor activation during exercises in these positions in comparison to others (Contreras *et al.*, 2015; Neto *et al.*, 2019; Macadam & Feser, 2019; Collazo Garcia *et al.*, 2019; Neto *et al.*, 2020). Finally, the considerations highlighted above were not necessarily recognised by the research group prior to the commencement of tool development. This can explain the ongoing developmental procedure that the HEB has followed.

Table 3.2. Framework of considerations for the development of a new assessment tool.

Consideration	Detail	Why is this important?
Contraction type	Dynamic vs. static and integrated vs. isolated movements	Practitioners must understand the desired action of interest (gross movement or specific muscle function). Environmental constraints (non-fatiguing measures) and/or capacity of interest (e.g. concentric force, angle specificity) should determine contraction mode selection
Level of measurement	Tool validity and reliability Tool clinical feasibility	Tool development should consider the field in which it is to be used. How sensitive does it need to be and what environmental restraints determine tool function?
Limb and joint positioning	Standardising methods of consistent joint position	Changing joint angle influences moment arm, normalised fibre length, regional muscle size, muscle and tendon stiffness and neural drive Precise joint angles must be reproducible so that a tool is assessing what it claims to be and cross-comparison between participants or trials can be made
Open vs. closed chain	Stability during MVIC assessment and transference to the field	Closed kinetic chain movement holds increased stability allowing greater opportunity for force application Closed kinetic chain movement may increase transference to on-field performance where distal segments are in contact with stable surfaces upon times of high muscle contraction
Direction and transference of movement	Specificity of movement during maximal force production Force-vector and dynamic correspondence theories	Orientation of body relative to direction of force production influences type of muscle recruitment and specific state of muscle during contraction. Anteroposterior loading suggested to hold facets more specific to sprint-acceleration performance than axial loading. Hip extension is a key capacity for sports performance and anteroposterior loading increases hip extensor recruitment across all given range of motions in comparison to axial loading
Location for acquisition of force	Assessing directly at the joint of interest	Indirect dynamometer positioning may increase the likelihood of unwanted muscle contribution across nearby joints Posteroanterior positioning seems to increase unwanted pelvic instability

3.2. Hip extension bench assessment tool development

The following section provides a description of each phase in the development of the HEB strength assessment and training tool which is to be utilised in the remainder of the thesis. Refinements of the HEB were made when either known considerations were not met sufficiently or the awareness of a new consideration arose throughout the developmental phases. These refinements allowed the tool development to continue until a point where confidence was met with the final tool that had been developed.

3.2.1. Phase 1

Upon commencement of the current groups research, an assessment of isometric strength deemed a measure of hip extension was already present within the collaborating football club assessment battery (figure 3.3). The assessment setup required participant to lay supine with feet elevated on a box and hips underneath a loaded weightlifting bar of over 200 kg of mass. Hip flexion angles were measured manually with a goniometer and foot position was altered until participants maintained a 60° angle whilst their hips were in contact with the bar. Portable force plates (PASCO Scientific Inc., California, USA) were placed on top of the box/underneath the feet. Participants were required to extend their hips to the bar in an attempt to displace the bar in a vertical direction relative to the floor, with the substantial load ensuring an isometric condition was held. The force was said to be assessed as the heels pushed down into the plate at the distal end of the lower limbs.

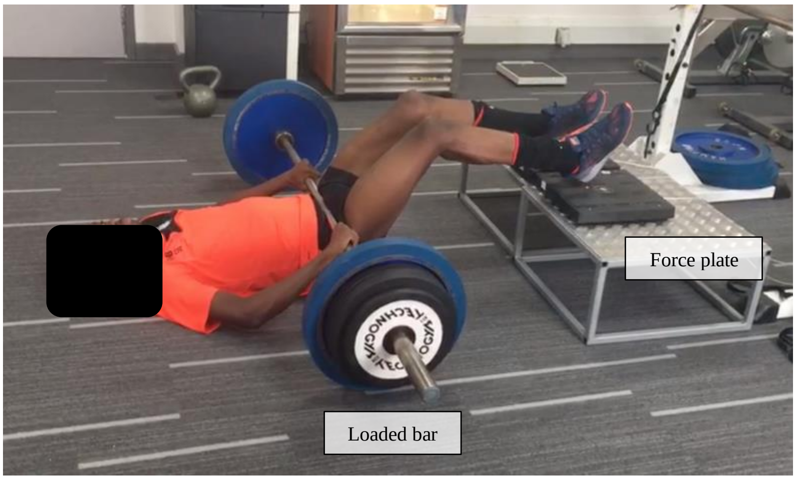
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Figure 3.3. Phase 1 of development of the hip extension bench assessment tool.

Upon utilisation of the assessment tool established in phase 1, various advantages and drawbacks arose surrounding a number of considerations discussed in section 3.1. (see table 3.3). One limitation deemed greatly significant by the research team was the inability to isolate hip because of the location for acquisition of force. With load acquisition positioned at the feet in this supine position it is biomechanically feasible to suggest that knee flexion would largely contribute towards force application to the force plates. Because of this and the various other drawbacks that were present in phase 1, inconsistencies occurred in data collection and it was decided that the research team would revisit the setup design and work towards a second phase of development.

Table 3.3. Advantages and disadvantages surrounding phase 1 of the HEB tool development, in respect to the considerations outlined in section 3.1.

Consideration	**Achieved?**	**Comments**
Contraction type	Yes/No	Yes - as long as force application occurred after the hips lifted to the bar an isometric condition should be present No – the multi-joint nature of the task does not isolate the hip extensor muscles, so should be deemed an integrated assessment
Equipment type	Yes	Force plates are commonly utilised in the applied field due to their accuracy, portability and ease of use
Limb and joint positioning	No	Hip angles are roughly confirmed with a manual goniometer upon hip lift to the bar. Knee angles are not measured or standardised and may differ significantly upon different athletes upper and lower leg length discrepancies
Open- vs. closed-chain	Yes	Closed-chain nature allows for increased stability and reduced coordination to increase the athletes force production capability
Direction of movement/force-vector	Yes	Force is applied in a horizontal / anteroposterior direction and requires a ground reaction force to be applied. However, the 60° angle does not necessarily coincide with the dynamic correspondence theory facet of accentuated region of force production.
Location for acquisition of force	No	Force data is collected at the heels which means that any joint moment activity at the knee will influence the output of force that is generated. This eliminates the possibility for an isolated hip extension force due to the addition of knee flexion/extension moments

3.2.2. Phase 2

In an attempt to eradicate some of the limitations of phase 1, a second assessment setup was developed. Utilising similar equipment to phase 1 a new setup was developed by integration into the organisations isometric mid-thigh pull setup. Within this setup athletes were again required to produce force in an anteroposterior direction against the immoveable bar with the added benefit of the capacity to standardise hip and knee angles (see figure 3.4).

Figure 3.4. Phase 2 of the hip extension bench development.

Within phase 2 of development, maintaining a 90° knee angle perpendicular to the floor meant that contribution of force from the knee flexors/extensors would be minimised and joint angle consistency would stabilise. Here it was hypothesised that the location for force acquisition limitation in phase 1 would be eradicated. With that being said, upon implementation of the new setup further limitations arose, as are outlined in table 3.4. The primary limitation during phase 2 was the location of force acquisition at the feet insufficiently representing isolated isometric hip extension strength. The indirect location of force acquisition meant that the total force applied to the bar was distributed disproportionately to the proximal and distal points of contact, the force plate and the back rest. In some cases, the stronger athletes (those able to lift the whole rig equipment) produced some of lowest scores against the force plate due to perhaps transferring a greater proportion of force to the back rest instead of the force plates. For these reasons, a third phase of development was attempted.

Table 3.4. Advantages and disadvantages surrounding phase 2 of the HEB tool development, in respect to the considerations outlined in section 3.1.

Consideration	**Achieved?**	**Comments**
Contraction type	Yes / No	Yes - as long as force application occurred after the hips lifted to the bar an isometric condition should be present No – environmental constraints meant that the rig could not be held to the ground for stronger athletes, eliminating the true isometric nature of the task
Equipment type	Yes	Force plates are commonly utilised in the applied field due to their accuracy, portability and ease of use
Limb and joint positioning	Yes	Hip angles are confirmed with an adjustable bench of 10° increments. Knee angles are standardised as perpendicular to the floor creating a 90° angle
Open- vs. closed-chain	Yes	Closed-chain nature allows for increased stability and reduced coordination to increase the athletes force production capability
Direction of movement/force-vector	Yes	Force is applied in a horizontal / anteroposterior direction and requires a ground reaction force to be applied. The adjustable bench can alter hip flexion angle to coincide with the dynamic correspondence theory facet of accentuated region of force production, depending on the goal in interest
Location for acquisition of force	No	Force data is collected at the heels and the axis of rotation is at the hip. Therefore, force is transferred both proximally (back against backrest) and distally (heels against force plate) and unless force is collected at both ends, the total force output cannot be estimated from a single measurement site. Athletes were found to employ different techniques and differ in their proportion of force production against the force plate and back rest

3.2.3. Phase 3 (the Hip Extension Bench)

In order to successfully overcome limitations that are present in previous versions of the HEB it was concluded that assessing maximal hip extension strength would only be valid if the position of force acquisition was directly placed at the hips. This point was believed to render the use of force plates as impossible and required the research team to turn to an alternative type of equipment. Load cells are a type of force gauges typically used in industrial environments for weighing heavy items. Due to their portability and ability to accurately and reliability assess isometric force (Barbosa *et al.,* 2015; Bellar *et al.,* 2015), load cells have begun to be used within the area of strength assessment in sports science. For example, developers of the NordBord (Vald Performance, Newstead, Australia) initially utilised an MLP-1K load cell placed above the posterior side of the ankle to assess strain or the "pulling forces" as the athlete completes an eccentric Nordic hamstring exercise or a knee flexion MVIC (figure 3.5). Ultimately this was further developed into the NordBord device (Opar *et al.,* 2013). S-type load cells have also been used to recreate a portable version of the isometric mid-thigh pull (James *et al.,* 2017) as shown in figure 3.6.

Figure 3.5. MLP-1K load cells utilised in a tool to assess eccentric and isometric hamstring strength.

Figure 3.6. S-type load cells utilised to assess isometric vertical strength in an IMTP setup.

Development of HEB was completed by an initial collaboration with the universities mechanical engineering department. Here a discussion surrounding needs analysis enabled the researchers to trial setups and select the most suitable load cells (see figure 3.7).

Figure 3.7. Equipment selection process at the collaborating universities mechanical engineering department.

After subsequent acquisition of the required load cells a full development of the finalised HEB apparatus was confirmed (figure 3.8) and successful adherence of the considerations presented in 3.1. are outlined in table 3.5 below.

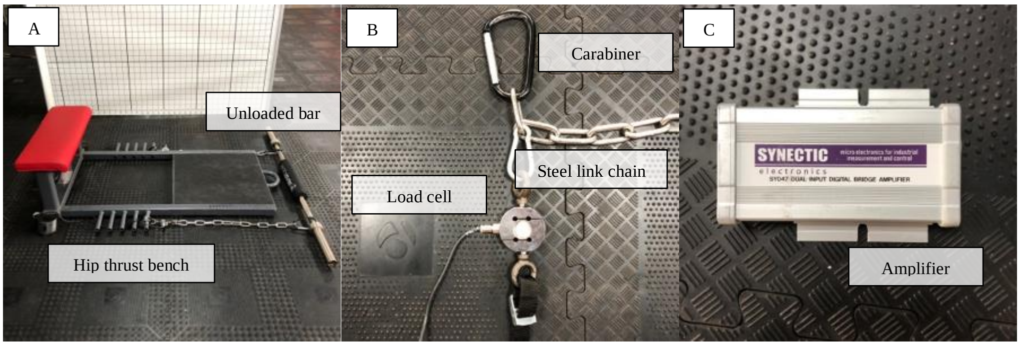

Figure 3.8. The hip extension bench assessment tool setup. (A, the hip extension bench with all connecting parts. B, the load cell, steel link chain and carabiner required for attachment to the bar. C, the amplifier connecting the load cell to the computer).

Table 3.5. Advantages and disadvantages surrounding phase 3 of the HEB tool development.

Consideration	Achieved?	Comments
Contraction type	Yes	Yes - as long as force application occurred after the hips lifted to the bar an isometric condition should be present
Equipment type	Yes	Load cells are portable, easy to utilise and fast to setup
Limb and joint positioning	Yes	Hip and knee angles are accurately confirmed by means of Pythagoras and trigonometry
Open- vs. closed-chain	Yes	Closed-chain nature allows for increased stability and reduced coordination to increase the athletes force production capability
Direction of movement/force-vector	Yes	Force is applied in a horizontal / anteroposterior direction and requires a ground reaction force to be applied. The easily adjustable bar height can alter hip flexion angle to coincide with the dynamic correspondence theory facet of accentuated region of force production, depending on the goal in interest
Location for acquisition of force	Yes	Force data is collected directly at the hips. Such a position reduces contribution of force from muscles surrounding other joints.

3.3. Hip extension bench assessment tool application

The final section of chapter 3 seeks to provide the reader with practical recommendations for application of the HEB assessment and training tool. A comprehensive description of the apparatus and setup procedures are first introduced which seeks to outline the specific selection of equipment and intricacies surrounding accurate joint angle quantification and standardisation. Following this, a detailed description of the authors recommended assessment protocol is outlined inclusive of a warmup, assessment execution and technical cues to utilise. Finally, recommendations for utilising the HEB for isometric training are given. This information should remind the reader of the importance robust methodologies for reducing error and subsequently improving the validity and reliability of the HEB setup.

3.3.1. Assessment tool setup

Apparatus. As pictured in figure 3.8 of 3.2.3 a hip thrust bench (Perform Better, Southam, UK) is utilised to provide stability at both proximal (posterior torso) and distal (feet) ends during the CKC movement. An unloaded 10 kg weightlifting bar is placed across the participant's pelvic region and connected to the hooks at the base of the bench. This connection is made via two steel link-chains and carabiners, attached at either side of the participant to the grip section of the bar and the hooks of the hip thrust bench. Connecting the two chains on either side are two 5 kn TSA load cells (Techni Measure Ltd, Doncaster, UK) and for comfort around the pelvis, a foam pad can also be attached to the weightlifting bar. Justification for the use of a *hip thrust-like* setup for the HEB is largely based on its ability to successfully adhere to the considerations presented above. It is also based upon the wealth of research surrounding the hip thrust for lower limb posterior chain activation and training, as evidenced in previous sections. Furthermore, Macadam & Fesir (2019) systematically reviewed G_{max} excitation across 25 exercises deemed to have a vertical force vector, 14 exercises in the horizontal anteroposterior force vector and 38 exercises deemed to have a horizontal posteroanterior force vector. Within this analysis, the single leg bridge was deemed the exercise in the anteroposterior direction with the highest G_{max} excitation (51 % MVIC).

The inclusion of a foam bar pad was deemed necessary due to comfort reasons as maximal isometric contractions against a steel bar was not suitable. Material density was the primary factor requiring attention on bar pad selection as to minimise loss of force through energy absorption and to minimise joint angle changes due to deformation of the pad. It was the research groups belief that inclusion of a bar pad holds more advantages than drawbacks in comparison to no bar pad as individuals were reluctant to produce maximal force against a steel bar.

Joint angle setup and limb alignment. In order to quickly and accurately determine precise hip angles whilst maintaining a 90° knee angle a comprehensive excel spreadsheet was developed. The following equations complete the excel document that with iteration via a goal-seek function can provide exact heel placement and bar height values that are specific to each individual athlete. Iteration is a mathematical method where repetition of a process is completed in order to generate a sequence of outcomes. In this case, the outcome is the hip angle, foot placement and bar height and the athlete and equipment dimensions are the input. Following these procedures will enable assessment of isometric hip extension strength at any desired angle (see figure 3.10.a and 3.10.b).

Calculating hip angles. Calculation of hip and knee angles for each HEB position is completed with the mathematical formulas of Pythagoras theorem and trigonometry (figure 3.9). This process allows better precision of angle determination in comparison to a manual goniometer and reduces the time-cost per athlete assessment. Initially, collecting tool and athlete dimensions are required for use within the hip and knee angle calculations.

Tool dimensions. On figure 3.11, length *AF* (in cm) is the height of the backrest to the base of the hip thrust bench. To account for the average athletes' thoracic depth in the vertical direction an additional 5 ± 1.25 cm is added, where the ± 1.25 provides a range for larger and smaller athletes. These representative values were determined in an adult cohort of fitness coaches. Length *AB* (in cm) is the distance between the base of the backrest and the hook at the base of the load cell, minus 11 cm to account for the projecting backrest. Again, 5 ± 1.25 cm is added to account for the average athlete's thoracic depth, this time in the horizontal direction.

Athlete dimensions. Length *ED* is the distance between the greater trochanter of the hip and the lateral epicondyle of the femur. Length *DC* is the distance between the lateral epicondyle of the femur and the lateral-posterior surface of the calcaneus. Both of these values are to be determined by experienced practitioners in the palpation of anatomical positions. The above dimensions within figure 3.9 were then included in the Pythagoras and trigonometric equations and solved by iteration (as shown below).

The distance between each hook on the base of the HEB is 6 cm. This allows the steel chains to be attached at different points if required, corresponding to different athlete torso lengths. The reference point for back placement against the back rest was mid scapulae region and chains were moved either forwards or backwards a hook to maintain a vertical chain from floor to hip to a precise accuracy of 3 cm (mid-point of each hook). Such considerations ensured that the external moment arm from the bar to the back rest was consistent for all athletes, relative to total body size.

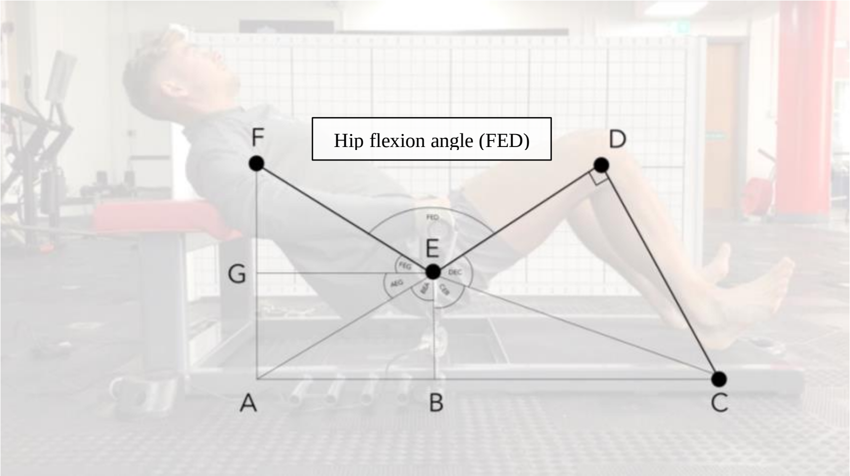

Figure 3.9. Dimensions of the HEB required to determine desired hip angles during assessment

Working example of HEB with a 70° angle (HEB$_{70}$):

Device and athlete dimensions:
Angle, 70° (HEB$_{70}$)
AF, 41 + 1.25 cm
AB, 53 – 11 – 5 – 1.25 = 35.75 cm
ED = 45 cm
DC = 55 cm

1. $\angle$DEC = $\tan^{-1}\left(\frac{DC}{ED}\right)$ = 51°
2. $\angle$CEB = $\cos^{-1}\left(\frac{BE}{EC}\right)$, where length *BE* is to be calculated and length *EC* is $\sqrt{ED^2 + DC^2}$ = 75°
3. $\angle$BEA = $\tan^{-1}\left(\frac{AB}{BE}\right)$, where length *BE* is to be calculated = 63°
4. $\angle$AEG = $\tan^{-1}\left(\frac{BE}{AB}\right)$, where length *BE* is to be calculated = 27°
5. $\angle$GEF = $\tan^{-1}\left(\frac{AF-BE}{AB}\right)$, where length *BE* is to be calculated = 34°
6. $\angle$FED is 110 – 70, as we want the hip angle to be 70°.

To confirm correct calculations the sum of all angles should add up to 360°.


[redacted]

Figure 3.10.a. Bilateral isometric hip extension strength at 15° hip flexion (HEB_{15}) measured with the HEB assessment tool.


[redacted]

Figure 3.10.b. Bilateral isometric hip extension strength at 60° hip flexion (HEB_{60}) measured with the HEB assessment tool.

Data extraction. During assessment, the preferred means of MVIC collection was trialled within a purpose-built software interface (Synectic Design Ltd, Bolton, UK) prior to the data collection period in order to utilise the most robust and time-efficient method. Within the setup, the load cells were connected to via USB connection (figure 3.8) which converts the raw analogue signal to a digital one. A “hold” function was added to the software to allow channel’s 1 and 2 to present the highest force reading exerted during an

MVIC on screen. A “reset” and “tare” function was also added to quickly recalibrate the load cells to zero between repetitions. Further to this, it was decided that the rate at which numbers updated on the screen would be set to “continuous” and “infinite samples” in order to ensure that no readings were missed across the testing period. Each of these factors when implemented into the data collection procedure allows for practitioners to obtain quality data in short periods of time, which is especially useful during time-constrained situations of collecting information with multiple tests and/or athletes in one sitting.

For extraction of force data, values for both left and right load cells were manually inputted into a HEB data spreadsheet, unless there was a visible “spike” or fault in the load cell data presented on the software. This method of determining the peak values produced during MVIC’s was deemed the most useful due to its automation in identifying peak values and its ability to provide instant feedback for the athletes. At the time of data collection, the amplifier and software utilised functioned to record data at a sampling rate of 50 Hz from the load cell, yet upon extraction for further analysis of the raw force-time curves only 5 Hz could be obtainable in the csv. Because of the low sample rate on extraction, it was not possible to interpret the force-time slope relationship for an accurate estimate of RFD, so peak force (N) was the only obtainable variable.

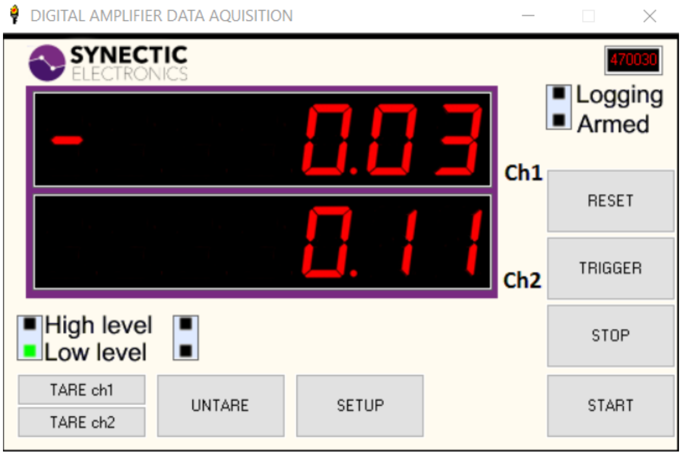

Figure 3.11. The software interface for the HEB assessment tool.

3.3.2. Data collection procedures

Assessment protocol. Assessments should be preceded by a comprehensive warm up to ensure the athlete is prepared to perform optimally. Upon execution, athletes are encouraged to complete all assessments barefoot to ensure within and between participant consistency and reduce the influence of footwear design may have on force production potential. This is not so necessary during training. A detailed explanation and order of suggested coaching cues is outlined in figure 3.12. below.

Procedures and directions prior to MVIC collection

Practitioner to acquire anthropometric measurements and fill into spreadsheet to determine foot placement and bar height

Athlete to be seated in HEB with mid scapula centered across back-rest and heel aligned at correct number. Ankles knees and hips aligned in parallel

Athlete directed to take a wide pronated grip and to “pre-tense” by extending their hips to displace the bar until chain-slack is removed

Practitioner to check chains are perpendicular to the floor and amend hook and foot position if necessary

Technical cues for the athlete prior to MVIC efforts:

1. “Aim to push your hips through the bar and towards the ceiling with your glutes and hamstrings”
2. “Aim to break the chains by pushing your hips as hard and fast as you can into the bar”
3. “Whilst doing this, keep a big chest, brace your core, keep your shoulders back and tuck your chin”
4. “Keep your toes up so only your heels are in contact with the mat”
5. “Hips up to the bar, 3, 2, 1…”

Verbal encouragement cues during MVIC for 3 to 5 seconds:

“Push, push, push…!”

Figure 3.12. Order of procedures, directions and cues during prior to and during MVIC data collection with the HEB.

3.4. Conclusion

The primary aims of this chapter was to introduce various considerations surrounding the development of successful strength assessment tools and to introduce the reader to the development of a new isometric hip extension strength assessment tool. It is of the research groups opinion that the HEB assessment tool successfully accounts for all considerations outlined in 3.1. and upon investigation should be deemed a valid and reliable hip extension assessment tool. Upon successful adherence to the various considerations outlined in 3.1. it is hypothesised that the HEB will provide a means of successfully representing an athlete’s maximal isometric hip extension force capacity. Additionally, alongside adherence of the concise instructions outlined in 3.3. it is hypothesised that random error will be minimised, thereby improving test validity and reliability. As such, further investigations are necessary to determine the suitability of the HEB assessment tool for successful implementation into the applied world of sports science.

Chapter 4

The sensitivity of the hip extension bench to detect changes in force production and muscle activity across various angles of hip flexion/extension

4.0. Interlude

Information within chapter 2 and 3 of the thesis confirmed the crucial importance of valid and reliable assessment and training tools. Having confirmation of a tool successfully assessing or exercising its intended muscle or joint action ensures that the desired outcome of a task is possible. In applied terms, practitioners assessing what is believed to be a maximal hip extension strength need confidence that the muscles deemed hip extensors are the ones that contribute to the single measure of peak force that is provided as an output. Otherwise incorrect information may confuse or disinform decision making. From a training perspective, recruitment of the correct muscles during execution of a task is essential in order to ensure that sufficient mechanical stress and overload is applied to promote muscle adaptation.

The previous chapter detailed a series of considerations that are believed to be crucial factors for the development of a new assessment tool of isometric hip extension strength. Upon successful adherence to these considerations it is believed that a valid and reliable tool will stand that is superior to previous assessment types and more suited for application in the field of elite sport. Consequently, it would seem logical for the next steps of research to investigate the validity and reliability of the tool prior to its implementation for exploratory purposes. However, traditional steps of validating the HEB assessment tool become difficult when the “gold standard” measure is believed to be inadequate. As such, it seems inappropriate to make comparisons between a new assessment and one who’s drawbacks have driven the development of the HEB itself. Therefore, instead of seeking to achieve validation, the following chapter attempts to evaluate the HEB assessment tool’s successful adherence of the framework of considerations outlined in chapter 3. For instance, by understanding the sensitivity of the HEB to detect change in hip extensor behaviour across various hip flexion angles, the importance of limb and joint positioning as a consideration will be confirmed. This information will also provide the research team with some information surrounding selective activation of individual hip extensor muscles to inform future decisions of measuring isometric hip extension strength at specific joint angles.

4.1. Introduction

As detailed in chapter 3, hip extension behaviour is significantly influenced by various changes in limb and joint positioning. These changes can arise from angle adjustments in hip flexion/extension (Németh & Ohlsen, 1985; Ward *et al.,* 2010; Visser *et al.,* 1990; Worrell *et al.,* 2001; Bazett-Jones *et al.,* 2017; Dostal *et al.,* 1986; Neumann, 2010), internal/external rotation and abduction/adduction (Suehiro *et al.,* 2014; Kang *et al.,* 2013; Sakamoto *et al.,* 2009; Colazzo-Garcia *et al.,* 2018), knee flexion/extension (Kwon *et al.,* 2013; Sakamoto *et al.,* 2009) and pelvic tilt and trunk stabilisation (Queiroz *et al.,* 2010; Kim & Seo, 2015; Tateuchi *et al.,* 2012; Choi *et al.,* 2015; Oh *et al.,* 2007; Kim *et al.,* 2014). Research to date has confirmed that all of the above are able to influence hip extensor muscle behaviour on an individual level and as a gross joint action of force and/or torque production due to several physiological and biomechanical properties related to the musculoskeletal system. Therefore, when assessing this joint action, it is hypothesised that concise methods of standardising setup procedures are crucial for consistent acquisition of data under repeatable conditions. Without this, it becomes hard for practitioners to make inferences on the data, when a change in the test output may arise from small differences in joint angle, muscle length or moment arm, as opposed to homeostasis of the athlete.

Considering the primary influence that hip flexion has on muscle length and moment arm (Németh & Ohlsen, 1985) of the hip extensor muscles, it seems important to understand to what extent this may influence muscle behaviour and resultant force production. The influence of hip flexion angle in particular on hip extension force has been recently investigated during prone isometric hip extension (Bazett-Jones *et al.,* 2017), yet research surrounding muscle activity changes is limited. Worrell *et al.* (2001) significant changes in G_{max} muscle activity during prone isometric hip extension but no specific changes in hamstring muscle activity with collection of a single measure of grouped hamstrings behaviour.

Understanding the influence of hip flexion angle on hip extensor muscle behaviour is important in order to determine the extent of precision for limb and joint positioning during collection of isometric hip extension strength measures. Realising and applying these precisions will reduce the random error of the assessment tool and will allow for greater confidence in interpreting meaningful change in response to an acute or chronic stimulus of exercise. However, if such investigations are not understood the multifactorial nature of influences to muscle activity and force production can provide great confusion. Whether specific changes in individual muscle behaviour and joint action are present during hip extension at different hip flexion angles may also inform practitioners for targeting specific assets of hip extension during assessment. For instance, Bazett-Jones *et al.* (2017) suggested positions of low hip flexion to be chosen when the goal is to isolate the G_{max} muscle during hip extension assessment.

Aside assessment purposes, the same can be applied for training prescription. If specific muscle behaviour is present at different angles, a rationale to train the hip extensors under isometric conditions at specific angles could be developed. For example, considering reduced G_{max} force production has been associated with reduced repeated sprint ability (Edouard *et al.,* 2018), having the capacity to target the G_{max} muscles in isolation could be of benefit to improve this important capacity.

Investigations surrounding the onset and amplitude of G_{max} activity during exercise have confirmed inefficient activation of the G_{max} to increase an athlete's susceptibility to HSI during sprint-acceleration efforts (Schuermans *et al.,* 2017b). This is due to the fact that the hamstrings might be exposed to increased mechanical output when the supporting proximal muscles do not function in time. As such, it may also be interesting to understand whether there is an optimal G_{max}: hamstring onset and/or magnitude ratio for the prevention of HSI. In addition, it may be of interest to determine whether these findings follow uniformity across various hip flexion angles or whether a desired level of G_{max} and hamstring muscle function is present at different muscle lengths.

A considerable amount of limitations were presented in chapter 3 surrounding assessment methods that have been utilised to previously investigate hip extension strength. As such, findings from the literature surrounding hip extensor muscle activity and joint action become difficult to interpret. For this reason, the current researchers believe that it would be of benefit to reinvestigate the topic with the HEB assessment tool that is hypothesised to be a more suitable alternative to the previous measures. Such an investigation will at least add to the little information that is currently available.

Therefore, the primary aim of the present study is to investigate the sensitivity of the HEB assessment tool to detect change in individual hip extensor muscle activation and the force generating capacity of the hip extensor during maximal isometric contractions under various angles of hip flexion. According to currently available research, it was hypothesised that increasing hip flexion would present a marked increase in the force generating capacity of the hip extensors. Secondly, it is assumed that G_{max} muscle activity will be greatest in a shorter position towards full hip extension and that hamstring activity may present varied peak activity as assessment position changes.

4.2. Methodology

4.2.1. Participant characteristics

Ten elite youth soccer players, ten competitive sprinters and five recreationally active males volunteered to take part in the study (participant characteristics summarised in table 4.1). Inclusion criteria involved individuals being free from lower limb pain and/or injury in the past 6 months that left them unable to participant in exercise, training sessions and/or competitive matches for a period of at least 7 days. The recruitment of sprinters was made due to their specialisation of sprint-acceleration performance and subsequent risk for HSI that comes with the sport, two areas that hip extension may help with. Prior to data collection and analysis, it was decided that the three cohorts would be grouped in order to hold a larger sample size (n = 25) unless significant differences were found between cohorts. Dominant leg was determined by which foot was preferred to kick a ball with (van Melick *et al.* 2017) and prior to testing all participants were provided with an information sheet, informed of potential risks of the procedures and were required to provide informed consent. The study was approved by the Liverpool John Moores University human research ethics committee which conforms to the ethical standards established by the Declaration of Helsinki.

Table 4.1. Descriptive characteristics of the full cohort and individual soccer athletes, sprinters and fitness coaches' groups.

Group	**Sample size (n)**	**Age (years)**	**Height (cm)**	**Body mass (kg)**
Full cohort	25	23.8 ± 4.6	178.5 ± 5.6	76.4 ± 8.2
Soccer athletes	10	20.0 ± 1.1	177.7 ± 5.4	73.5 ± 6.0
Sprinters	10	25.7 ± 4.0	180.4 ± 5.3	78.3 ± 10.0
Fitness coaches	5	27.8 ± 4.6	177.1 ± 6.4	78.3 ± 8.5

4.2.2. Study design

Participants were required to visit the location of testing (Liverpool FC Academy, Kirkby, Liverpool, UK or Melwood Training Ground, Melwood, Liverpool, UK) on two separate occasions with a minimum of one-week and maximum of two-weeks between each visit. The HEB strength assessment tool was utilised to assess maximal isometric hip extension strength, as detailed below. Because of the novelty of the HEB assessment tool, the first visit required athletes to complete a comprehensive familiarisation session inclusive of several maximal contractions across two to three hip flexion angles (0-15°, 45° and 60-70°). The decision to familiarise athletes to two and not all HEB assessment positions was due to the clinical feasibility of data collection in a time-constrained field. As such, it was hypothesised that familiarising athletes with the most inner (0-15°) and outer (60-70°) extremes of the assessment would be viewed as sufficient. When time allowed, athletes were also familiarised with a midrange HEB assessment position (45°). During this time athlete body composition characteristics and leg measurements were also collected. The second visit comprised of the comprehensive analysis of hip extension strength performance across 6 different hip flexion angles ($HEB_{70,60,45,30,15\&0}$). Prior to the commencement of assessments, athletes were setup to the portable sEMG system and required to complete a standardised warm up consisting of cycle ergometer spinning, dynamic stretches and activation exercises. Upon completion of the warm-up participants had two practice attempts at the first assessment angle before completing a minimum of two maximum voluntary isometric contractions (MVIC) for each position. The duration of each MVIC was for a minimum of 3- and maximum of 5-s and participants were instructed to contract as hard and fast as possible against the bar. It was also instructed to push the hips through the bar and nothing else as to minimise pushing or pulling with the feet. During the assessment battery, participants were also given two practice attempts prior to the unilateral assessments. Within each assessment position a third repetition was required when the athlete either produced more force on their second attempt or felt they could improve with a third attempt. The order of assessment was randomised through assigning each HEB position a number and rolling a dice. Between repetitions and assessment positions a minimum of 15- and 120-s rest was given, respectively. The rationale for choosing a minimum of 15-s rest was to increase the clinical feasibility and ecological validity of data collection in time constrained fields where large rest periods are not often possible with large cohorts of athlete.

4.2.3. Force acquisition

As indicated above, the HEB assessment tool was utilised according to the recommendations outlined in chapter 2 with 6 angles determined by the automatic methods in the excel spreadsheet developed by the current researchers. Raw force-time data was collected and exported in .csv format to a portable laptop and a “hold” function of peak force was displayed on the software to be noted down by the assessor and used for subsequent analysis. Due to the importance of rapid force development in sports performance the research team would’ve found high worth from collecting information on rate of force production with the HEB. However as stated in chapter 3, at the time of data collection it was believed that the tools did not have the capacity to do so.

4.2.4. Muscle activity acquisition

Equipment. A Noraxon portable lab system with a built in Mini DTS system with wireless electrode sensors was used for surface sEMG data collection. Bi-polar Ag/AgCl surface electrodes with an inter-electrode distance of 20 mm were positioned over the muscle bellies of the BF_{lh}, G_{max} and ST. Prior to electrode placement the skin was prepared via shaving, light abrasion with sandpaper, cleansing with an alcohol wipe (Hermens *et al.*, 2000) and marked with a permanent felt tipped pen. In order to accurately distinguish the ST from the semimembranosus, the lead researcher was trained by experts in the field on palpation and ultrasound techniques. The positions for electrode placement were also determined according to the guidelines provided by Surface EMG for the Non-Invasive

Assessment of Muscles (Hermens *et al.*, 2000). Prior to any data collection, the baseline signal quality was checked via a function built into the Noraxon software, where activity of less than 5 uV was deemed acceptable. This was performed with the athlete at complete rest upon five minutes of sensor application to allow the skin to reach stable electrical conditions. Raw EMG signals were recorded at 1500 Hz and sent in real time to a computer via Bluetooth for analysis. Upon collection, the EMG signal was band-pass filtered between at 10-500 Hz, fully rectified and smoothed with a root mean square algorithm with a 200 ms time window. EMG data was normalised to a mean peak of a 250 ms root mean square window across the greatest time of muscle activity.

Hardware and software handling. After initial data processing, repetition start points were identified manually by one researcher and maximum values were determined automatically by each repetition by a "find max marker" function in the Noraxon software. Subsequently each repetition had 5 markers, one start marker and four peak EMG markers, one for each muscle (figure 4.1). Following this, raw .csv files were exported where further data handling was completed on a computer programming software (R, Auckland, New Zealand) in order to subsequently extract the desired variables of interest.

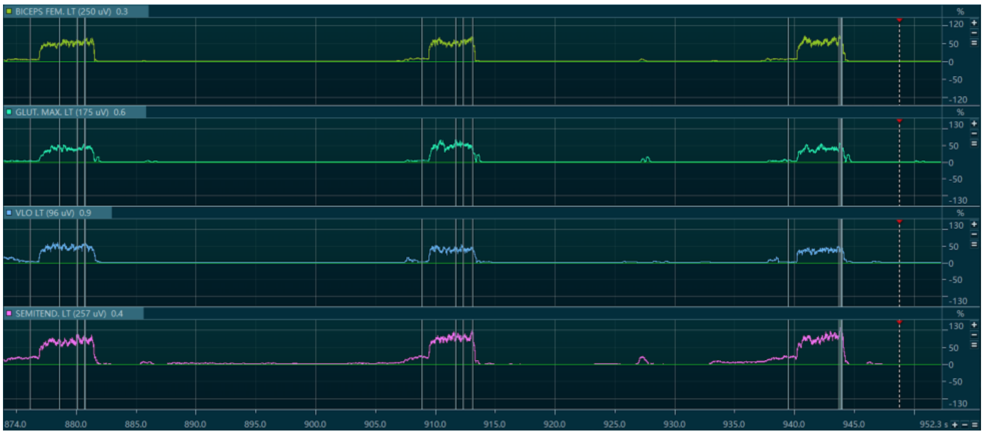

Figure 4.1. Four muscle excitation traces within the Noraxon software representing three MVIC attempts during HEB assessments. White vertical lines represent markers for each repetition.

MVIC determination. For each participant, the greatest EMG signal from a single effort was smoothed with a 250-ms root mean square window and taken as the reference contraction for all subsequent assessment positions. Each repetitions peak EMG measure was then represented as a percentage (%) of this contraction. For example, it was hypothesised that the G_{max} and hamstring would produce its peak EMG signal during the HEB_0 and HEB_{70}. In the instance of this being true, the best HEB_0 repetition would be classified as 100% and all subsequent repetitions and assessment positions would represent a percentage value relative to this. Similar normalisation techniques were also performed by Worrell *et al*. (2001).

4.2.5. Experimental variables

Peak force. Peak force (N) was determined as the maximum value at a single time point within an MVIC repetition.

Peak EMG. As a measure of the amplitude of individual muscle activity, peak EMG was determined by the greatest 200 ms root mean square smoothed window for each muscle after the processing described above.

EMG onset activation patterns. Individual muscle onset times were calculated using a 3 standard deviation threshold that was determined by a 500 milliseconds window according to previous recommendations (Schuermans *et al.,* 2017b). The 3 standard deviation threshold to cross was derived from the manually placed start marker mentioned above. During this time, muscle excitation was at a steady level after the "hips up to the bar" cue was given prior to maximal contraction. At this point, the marker was placed at the muscles "baseline state" EMG level approximately 750 milliseconds prior to contraction in order to determine an onset threshold value (figure 4.2). Once the muscles' activity surpassed and maintained above the 3 standard deviation threshold the EMG onset time value was determined. To represent findings of onset time, each muscle will be assigned a number representing the time from the first muscles onset threshold pass time to its own threshold pass time.

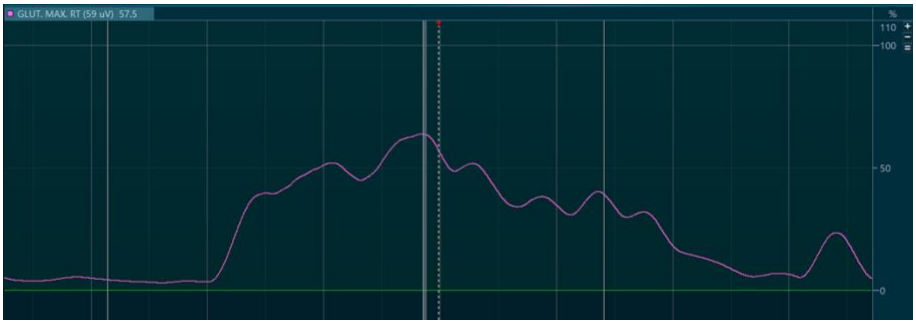

Figure 4.2. One muscle excitation trace (G_{max}) within the Noraxon software representing an MVIC attempt during HEB assessment. Excitation trace either side of the first white vertical line represents the "baseline state" used to derive the onset threshold value.

Average EMG. As a measure of total muscle contribution to per repetition, average EMG was determined for each individual muscle. The start marker for the average EMG calculation was the same marker as the 3 standard deviation onset threshold marker. The end marker was derived from the coding system that represented the time that muscle activity dropped and maintained below 20% of the peak EMG for that repetition, respectively. The sum of each data point was then divided by the total time between the onset and offset threshold markers to give a value of average EMG.

4.2.6. Statistical analysis

Descriptive statistics are displayed as means ± SD unless otherwise stated. A preliminary independent samples t-test analysis was performed to determine the average between muscle EMG onset time irrespective of HEB position. Each dependent variable was analysed with a one-way repeated measures ANOVA to detect angle-dependent differences at the 6 different positions ($HEB_{70,60,45,30,15\&0}$). Following significant effects for hip flexion, Bonferroni's correction post-hoc test was used to identify the independent significance of muscle activity and grouped force at each hip angle. Statistical significance was set to $P < 0.05$ and all statistical analyses were performed in SPSS 26.0 (IBM SPSS Statistics, Version 26, Armonk, NY, USA).

4.3. Results

4.3.1. Descriptive statistics

Table 4.2 presents the means and standard deviations for the force and EMG data across the 6 hip flexion angles.

Table 4.2. Descriptive statistics for the force and EMG data during HEB assessments across hip flexion 6 angles

Variable	**HEB$_{0}$**	**HEB$_{15}$**	**HEB$_{30}$**	**HEB$_{45}$**	**HEB$_{60}$**	**HEB$_{70}$**
Peak force (N)						
	1044 ± 345	1239 ± 345	1441 ± 346	1573 ± 342	1694 ± 342	1792 ± 410
Peak EMG (% MVIC)						
G_{max}	77.7 ± 13.5	74.9 ± 18.9	73.3 ± 21.5	67.3 ± 15.5	60.4 ± 19.8	60.6 ± 18.1
BF_{lh}	59.7 ± 16.0	70 ± 19.0	72.3 ± 17.7	73.3 ± 15.6	78 ± 13.9	75.7 ± 14.0
ST	65.1 ± 18.0	69 ± 19.5	71.3 ± 14.4	73.5 ± 14.7	78.5 ± 12.8	83.6 ± 13.0
Average EMG (% MVIC)						
G_{max}	55.8 ± 12.4	54.8 ± 15.9	52.7 ± 18.0	49.1 ± 14.4	43.1 ± 16.3	41.4 ± 15.4
BF_{lh}	46.7 ± 14.8	51.9 ± 16.3	55.2 ± 15.2	57.1 ± 13.1	60.2 ± 13.4	58.4 ± 13.4
ST	45.2 ± 16.4	50.9 ± 17.0	53.8 ± 14.1	55.2 ± 12.6	59.9 ± 12.2	62.7 ± 13.3
EMG onset time (% MVIC)						
G_{max}	0.18 ± 0.19	0.17 ± 0.14	0.21 ± 0.20	0.23 ± 0.16	0.18 ± 0.14	0.18 ± 0.14
BF_{lh}	0.09 ± 0.11	0.12 ± 0.11	0.11 ± 0.12	0.16 ± 0.16	0.10 ± 0.11	0.16 ± 0.15
ST	0.10 ± 0.11	0.14 ± 0.11	0.14 ± 0.12	0.14 ± 0.14	0.12 ± 0.12	0.16 ± 0.13

Table 4.3 presents the ANOVA results from the statistical analysis for all force and EMG variables.

Table 4.3. Statistical results for the influence of changing hip flexion angle on force and activation of the hip extensor muscles (ANOVA and Bonferroni's post-hoc analysis).

Muscle	**Hip Flexion (°) during MVIC hip extension**	
	ANOVA	Bonferroni's post-hoc ($P < 0.05$, $P < 0.01$*)
Peak force (N)		
	$F_{5,144}=15.79$, $P < 0.001$	HEB$_{70}$ > HEB$_{30,15*,0*}$, HEB$_{60}$ > HEB$_{15*,0*}$, HEB$_{45}$ > HEB$_{15,0*}$ and HEB$_{30}$ > HEB$_{0}$
Peak EMG (% MVIC)		
G$_{max}$	$F_{5,141}=3.97$, $P = 0.002$	HEB$_{70,60}$ < HEB$_{0}$
BF$_{lh}$	$F_{5,143}=3.79$, $P = 0.003$	HEB$_{70,60*}$ > HEB$_{0}$
ST	$F_{5,137}=4.28$, $P = 0.001$	HEB$_{70}$ > HEB$_{15,0*}$
Average EMG (% MVIC/s)		
G$_{max}$	$F_{5,141}=5.98$, $P < 0.001$	HEB$_{70}$ < HEB$_{30,15*,0*}$ and HEB$_{60}$ < HEB$_{15,0*}$
BF$_{lh}$	$F_{5,143}=3.78$, $P = 0.003$	HEB$_{70,60}$ > HEB$_{0}$
ST	$F_{5,137}=5.68$, $P < 0.001$	HEB$_{70}$ > HEB$_{15,0*}$ and HEB$_{60}$ > HEB$_{0*}$
EMG onset time (s)		
G$_{max}$	$F_{5,141}=1.03$, $P = 0.401$	N/A
BF$_{lh}$	$F_{5,143}=0.34$, $P = 0.889$	N/A
ST	$F_{5,137}=0.74$, $P = 0.594$	N/A

4.3.2. Peak force

Peak force was significantly influenced by hip flexion during isometric hip extension ($P < 0.01$) and post-hoc analysis revealed differences among testing positions (see table 4.3.). Peak force decreased as hip flexion decreased, with significance reached at HEB$_{30}$, HEB$_{15}$ and HEB$_{0}$ relative to HEB$_{70}$, HEB$_{15}$ and HEB$_{0}$ relative to HEB$_{60}$, HEB$_{15}$ and HEB$_{0}$ relative to HEB$_{45}$ and HEB$_{0}$ relative to HEB$_{30}$. Each of which were reached significance of $P < 0.01$ other than HEB$_{15}$ relative to HEB$_{45}$ ($P < 0.05$) (figure 4.3.)

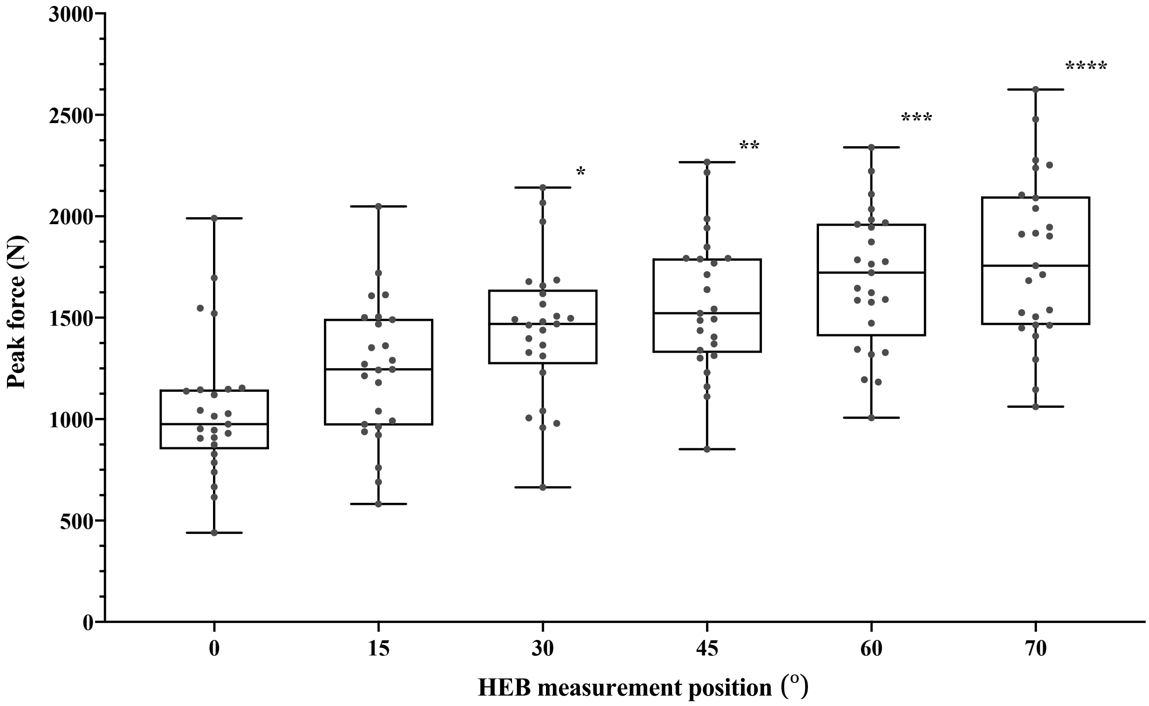

Figure 4.3. Peak force of the hip extensors during MVIC on the HEB across 6 angles (°) of hip flexion. Box plots represent the mean and 95% confidence intervals and whiskers represent the minimum and maximum values. Scattered points indicate the raw scores for each athlete (significance indicated by * = HEB_{30} > HEB_{0}, ** = HEB_{45} > $HEB_{15,0*}$, *** = HEB_{60} > $HEB_{15*,0*}$ and **** = HEB_{70} > $HEB_{30,15*,0*}$, where "*" indicates $P < 0.01$).

4.3.3. Peak EMG

Peak EMG was also significantly influenced by hip flexion during isometric hip extension for the BF_{lh}, ST and G_{max} muscles ($P < 0.01$). Peak EMG of the BF_{lh} and ST increased alongside increases in hip flexion with significance reached at HEB_{70} ($P < 0.05$) and HEB_{60} ($P < 0.01$) relative to HEB_{0} and HEB_{70} relative to HEB_{15} ($P < 0.05$) and HEB_{0} ($P < 0.01$), respectively (see table 4.2). Peak EMG of the G_{max} decreased alongside increases in hip flexion with significance reached at HEB_{0} relative to HEB_{70} and HEB_{60} ($P < 0.05$) (figure 4.4).

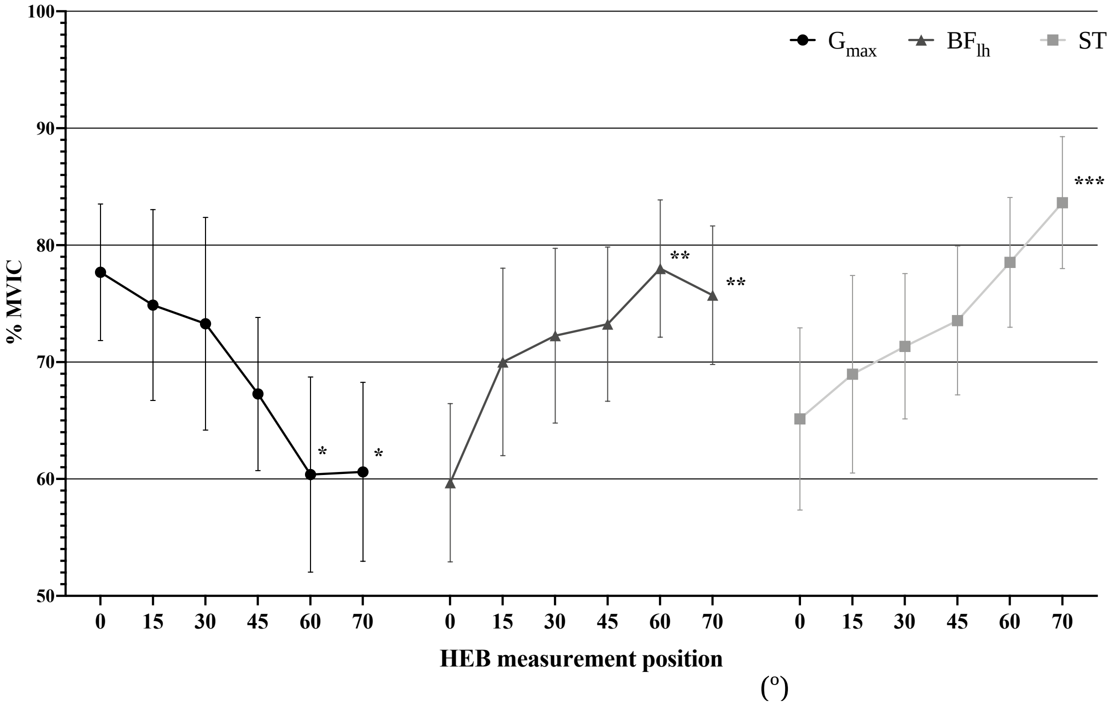

Figure 4.4. Peak EMG for the G_{max}, BF_{lh} and ST across each HEB assessment position (°). Error bars represent 95% confidence intervals (significance indicated by * = $HEB_{70,60}$ < HEB_0, ** = $HEB_{70,60*}$ > HEB_0 and *** = HEB_{70} > $HEB_{15,0*}$, where "*" indicates $P < 0.01$).

4.3.4. Average EMG

Average EMG showed similar findings to peak EMG as it was significantly influenced by hip flexion during isometric hip extension for the BF_{lh}, ST and G_{max} ($P < 0.01$). Average EMG of the BF_{lh} increased alongside increases in hip flexion with significance reached at HEB_{70} and HEB_{60} relative to HEB_0 ($P < 0.05$). Average EMG of the ST also increased alongside increases in hip flexion with significance reached at HEB_{70} relative to HEB_{15} ($P < 0.05$) and HEB_0 ($P < 0.01$) and HEB_{60} relative to HEB_0 ($P < 0.01$). Average EMG of the G_{max} decreased alongside increases in hip flexion with significance reached at HEB_0 and HEB_{15} ($P < 0.01$) and HEB_{30} ($P < 0.05$) relative to HEB_{70} and at HEB_0 ($P < 0.01$) and HEB_{15} ($P < 0.05$) relative to HEB_{60} (see figure 4.5).

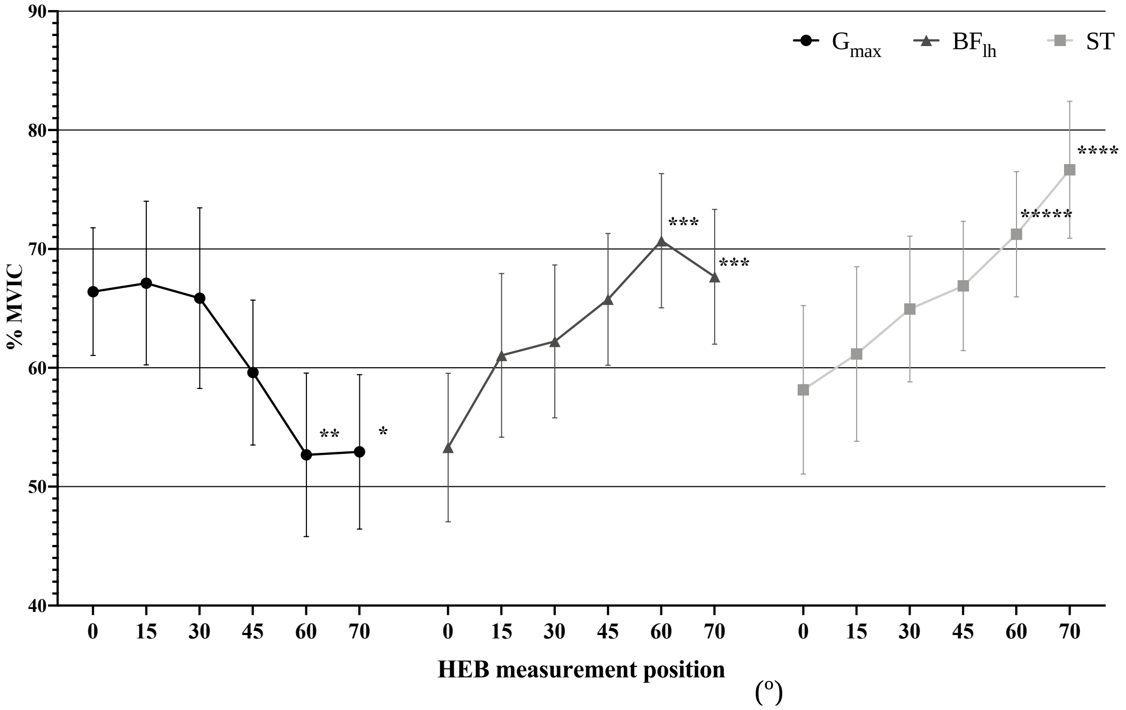

Figure 4.5. Average EMG for the G$_{max}$, BF$_{lh}$ and ST across each HEB assessment position (°). Error bars represent 95% confidence intervals (significance indicated by * = HEB$_{70}$ < HEB$_{30,15*,0*}$ ** = HEB$_{60}$ < HEB$_{15,0*}$, *** = HEB$_{70,60}$ > HEB$_{0}$, **** = HEB$_{70}$ > HEB$_{15,0*}$ and ***** = HEB$_{60}$ > HEB$_{0*}$, where "$_*$" indicates P < 0.01).

4.3.5. EMG onset time

The average EMG onset time across all HEB assessment angles for the participants was statistically different between G$_{max}$ and BF$_{lh}$ ($P < 0.01$) and G$_{max}$ and ST ($P < 0.05$) but not between BF$_{lh}$ and ST ($P = 0.33$). The onset time of the G$_{max}$ muscle was significantly later than that of the BF$_{lh}$ and ST muscle. These findings were true irrespective of HEB assessment position where the average G$_{max}$ muscle EMG onset time was consistently greater than the BF$_{lh}$ and the ST muscle (see figure 4.6).

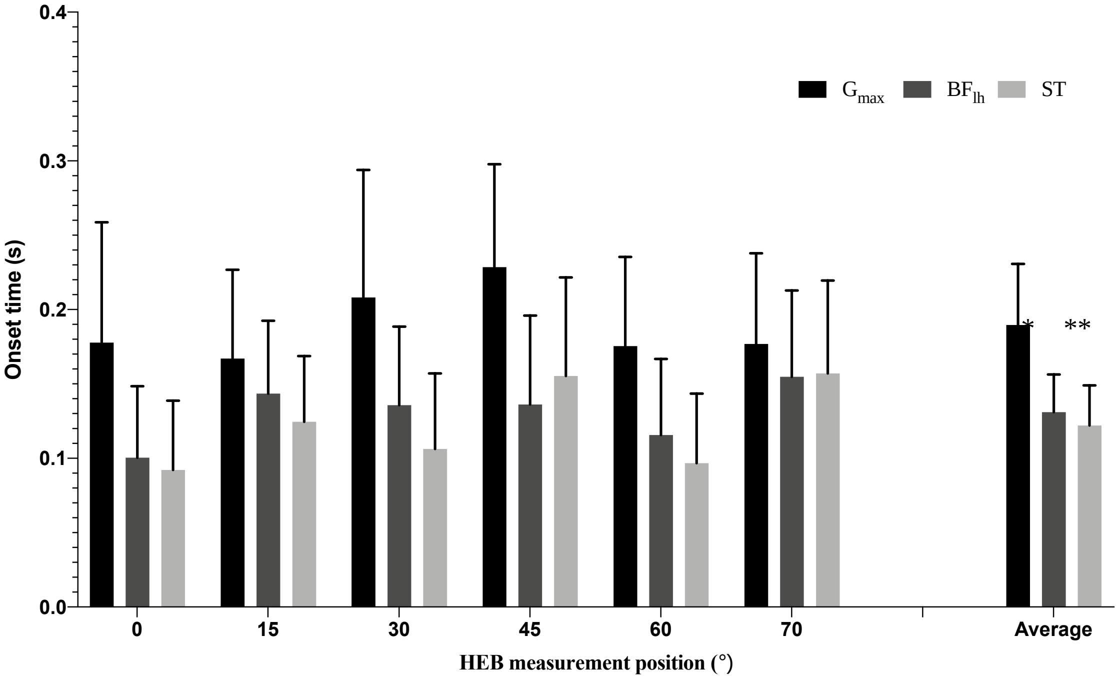

Figure 4.6. Average EMG onset time across each HEB assessment positions (°) and average across all positions (significance indicated by * = $BF_{lh} < G_{max}$, $P < 0.01$ and ** = $ST < G_{max}$, $P < 0.05$).

4.4. Discussion

The primary aim of the present study was to investigate how changing hip flexion angle effects activation and the force generating capacity of the hip extensor muscles under maximal isometric contractions. It was hypothesised that increasing hip flexion would present a marked increase in the force generating capacity of the hip extensors. Secondly, it is assumed that G_{max} muscle activity will be greatest in a shorter position towards full hip extension and that hamstring activity may present varied peak activity as assessment position changes. Therefore, the primary findings of the present study are somewhat in agreement with the research groups hypotheses, where assessment during the largest hip flexion angles (HEB_{70} and HEB_{60}) produced significantly more total force and muscle activity of the G_{max} when compared to positions of less hip flexion (predominantly HEB_{15} and HEB_0). Secondary findings presented for the first time a substantial and significant (at $HEB_{70/60}$ vs. $HEB_{15/0}$) increase in BF_{lh} and ST activity alongside hip flexion. Finally, investigations of EMG onset activation patterns displayed faster onset times of the hamstring muscles in comparison to the G_{max}.

Peak force

In agreement with the findings from the current study, previous literature has found maximum force/torque production during isometric hip extension tasks to be greatest under conditions of increased hip flexion, when compared to more hip extended angles (Bazett-Jones *et al.,* 2017; Worrell *et al.,* 2001). Albeit a different joint action, the same is also the case for conditions of increased hip flexion angles during knee flexion tasks (Guex *et al.,* 2012; Lunnen *et al.,* 1981; Mohamed *et al.,* 2002; Kellis *et al.,* 2017). Physiologically, there are numerous potential reasons for this significant increase. The G_{max} moment arm has been found to decrease alongside hip flexion increases, peak at 35-40° for the grouped hamstrings muscles and at 70-75° for the Add_{mag} muscle (Németh & Ohlsen *et al.,* 1985). As such, it may be postulated that the combined change in hamstring and Add_{mag} moment arms override the reduction in G_{max} moment arm and subsequently contribute to the increase in hip extension force production (Neumann, 2010). This may also indicate that the Add_{mag} becomes a substantially stronger hip extensor in positions of deeper hip flexion (Neumann, 2010). In addition, it can be suggested that the relative muscle length of the hip extensors is greater upon positions of hip flexion, leaving sarcomeres at a more optimal length-tension relationship for force production than when in a shortened state. This can be explained by the sliding filament model, where a greater number of myosin heads can attach to the actin filaments during muscle contraction via cross bridge links when sarcomere lengths are not too short or too long. Having said this, the researchers of the present study were unable to find studies investigating the muscle force length-tension relationship in vivo or via musculoskeletal modelling that demonstrate evidence of this. As such, it may be hypothesised but not scientifically confirmed that the increase in force/torque of the hip extensors during the hip flexed position may be due to a combination of a more optimal cross-bridge arrangement for the hip extensors and increase in moment arm for the Add_{mag}.

Peak and average EMG

Beginning with the hamstring muscles, the findings from the present study indicate an increase in peak and average EMG for the BF_{lh} and ST at HEB_{70} and HEB_{60} when compared to HEB_0 and HEB_{15} and HEB_0, respectively. Generally, previous literature observes no significant change in hamstring activation across changes in hip flexion angle (Worrell *et al.,* 2001) under similar conditions of 90° knee flexion. Albeit during knee flexion as opposed to hip extension assessment, increasing hip flexion angle also exhibits no significant change in peak activity BF_{lh} or ST muscles (Kellis *et al.*, 2017; Guex *et al.*, 2012). Regarding G_{max} activation, the findings of the present study are somewhat in agreement with that of Worrell *et al.* (2001) who also discovered a decrease in G_{max} peak EMG as hip flexion increased, albeit over a slightly greater range (0-90° vs. 0-70°). The increased range that Worrell *et al.* (2001) investigated may also reflect the slightly greater difference in peak EMG values that were exhibited (93-64 vs. 78-60 %).

Referring again to the sliding filament model theory, it may be suggested that sarcomeres within the hamstring muscles were in an extremely shortened state at HEB_0 and HEB_{15} positions. As such, muscle excitation may be reduced in comparison to positions of greater hip flexion, due to an absence of actin and myosin cross bridge alignment. Conversely, it seems appropriate to suggest as though the sarcomere arrangement in the G_{max} muscle are at a more optimal position when in inner range hip flexion, thereby increasing the muscles neuromuscular contractile potential.

Upon inspection, the specific magnitude of the peak and average EMG excitation values may be seen as quite low. The reason surrounding this is due to the fact that the normalisation process involved referencing each value to the peak value of the task at any HEB position. Further discussions of this factor and presented in the limitations section.

EMG onset activation patterns

EMG onset activation patterns in the current study seem to present relatively consistent findings for the order of muscle activation across HEB assessment position. Across all positions, the average G_{max} muscles onset time was significantly longer than it was for the BF_{lh} and ST muscles. These findings present some similarities to the findings from Schuermans *et al.* (2017a) who's two most common activation patterns during prone hip extension evidenced the hamstrings to activate first. These similarities are convincing considering the homogenous methodology of data acquisition between the two studies. Multiple other previous studies have examined muscle activation patterns during prone hip extension at various other hip positions (Bruno & Bagust, 2006; Kang *et al.*, 2013; Sakamoto *et al.*, 2009) and in general, it seems to be an agreement that the G_{max} is consistently the last activated muscle during hip extension tasks.

These findings may also present some similarities to those of Motomura *et al.* (2019) who discovered a preferential activation of the hamstrings muscle when combined hip extension and knee flexion was loaded in a prone position. These findings were especially true upon positions of increased knee flexion. It was discussed in the study that an increase in the neuromuscular activity of the hamstring may precede the synergistic contribution of the G_{max} muscle when loads are increased. Albeit the loading strategy and positional setup utilised within Motomura *et al.* (2019)'s study was considerably different to that of the present study, the findings may be somewhat comparable.

Limitations

The findings presented herein should be considered within the potential limitations of the study. As with all studies assessing the maximal force generating capacity of a muscle or group of muscles, it must be assumed that the athletes within the study applied maximum effort to every measure that was collected. Considering the number of trials that were required of the athletes, it may be reasonable to suggest that maximum effort was diminished at times during data collection. However, verbal encouragement, feedback on performance after every single effort and sufficient rest between repetition and position was given for every athlete. Furthermore, the order of HEB assessment positions was randomised for each athlete. Therefore, the researchers believe that limitations surrounding application or diminishing performance across the data collection period would be minimised.

In the present study, single dual electrodes were applied to the hamstrings' muscle belly at the midline between the proximal and distal palpation point of the muscle. A possible limitation to this is the inability to account for region-specific differences in muscle activation. For instance, previous research has discovered the hamstring muscles to have the capacity to selectively active specific regions of the muscle depending on the type of load that is applied to it (Tsaklis *et al.,* 2015; Bourne *et al.,* 2016; Mendez-Villanueva *et al.,* 2016; Schoenfeld *et al.,* 2016; Hegyi *et al.,* 2019). Therefore, during the isolated hip extension task, the activity in the proximal region of the hamstring muscles may have presented different behaviours to what it did in the present study. For instance, the sensitivity of the BF_{lh} muscle to changes in hip angle is greater than it is for the ST (Visser *et al.,* 1990). Therefore, it may be plausible to suggest that increased or decreased activity at proximal regions were not collected by electrodes placed at the midline of the muscle. As such it has been advised that multiple electrodes or multiple channel high-density electrodes are used in order to understand neural behaviour across the whole length of a muscle (Hegyi *et al.,* 2019).

A second limitation of the present study is the unavailability of a globally recognised method to use as a reference contraction. Within the present literature, there seems to be no agreement upon the best contraction type for eliciting maximal activation of the hip extensor muscles (Cochrane *et al.,* 2019; Contreras *et al.,* 2015). For this reason, it was decided that the greatest EMG signal from a single HEB assessment position effort would be taken as the reference contraction for all subsequent assessment positions. Unfortunately, a drawback of this reference technique is that it cannot be determined to what extent the hip extensors were activated compared to previous assessment types.

Another limitation of the present study was the inability to collect muscle activity data for the Add_{mag} muscle due to the intricate and awkward positioning of the muscle. Recently, the Add_{mag} has been proven as a potent hip extensor muscle (Benn *et al.,* 2018), which may reflect the fact that it is the second biggest muscle of the lower limbs (Ward *et al.,* 2010). As such, it cannot be confirmed to what extent the Add_{mag} muscle may have behaved across changing hip flexion and contributed towards the resultant force output.

A final limitation of the present study is the general limitations of sEMG and the specifics surrounding what can and cannot be inferred from EMG studies (Vigotsky *et al.,* 2018). Upon the processes of applying the EMG equipment to the athletes, every effort was ensured that the recommendations from Hermens *et al.* (2000) were closely followed in order to minimise signal interference. However, factors such as subcutaneous fat levels, sarcomere coverage under the skin and potential cross talk may still interfere with the quality of the data that is collected. Aside these limitations, Vigotsky *et al.* (2018) explained that a muscle that recruits motor units from deep to superficial will display a different sEMG amplitude-force relationship than would a muscle that recruits motor units from superficial to deep. As such, one cannot discern motor unit recruitment from rate coding using sEMG amplitude (Vigotsky *et al.,* 2018). However, as the methods in this study successfully adhered to, within-subject, within-muscle comparisons of the sEMG signal across different exercises may be able to provide insight into muscular force production, provided the previously mentioned controls are made. This is achieved by developing an understanding on whether the individual hip extensor muscles are “more” or “less” active in different positions of hip flexion.

Practical implications and conclusion

The findings from the present investigations can be used to provide a strong rationale for the importance of being concise with limb and joint positioning during the assessment of isometric hip extension with the HEB assessment tool. Considering peak force and muscle activity was significantly influenced by small changes in hip flexion, it can be suggested that every effort should be made to minimise error during data collection. Otherwise, the random error exhibited may cloud assessment results and leave practitioners incapable of making inferences from the data. Therefore, it is a great strength of the HEB assessment tool to be able to consistently determine hip flexion to the nearest 1° of accuracy.

Alongside this, results from this study can also be used to inform practitioners on the selection of joint angles to target specific muscles during assessment and training of isometric hip extension. On the basis of the results found in this study, it would be the researcher’s recommendations to utilise positions of greater hip flexion (HEB_{70} and HEB_{60}) to target neuromuscular recruitment of the hamstrings or hip extension force production at longer muscle lengths. In contrast, if targeting the G_{max} muscle, positions of lesser hip flexion (HEB_{0} and HEB_{15}) are recommended. Selectively targeting such positions may be useful for both performance enhancement purposes to mimic positions of ground contact ($HEB_{0\&15}$) and for injury management purposes to target positions similar to the late swing phase of gait ($HEB_{60\&70}$), for example.

Finally, to the authors knowledge this was the first investigation to present findings of consistently slower G_{max} EMG onset relative to the hamstring muscles across various angles of hip flexion. To date, it remains inconclusive on whether it may be preferential to increase the timing of G_{max} excitation for physical performance and injury prevention, yet findings from this study may be used as a baseline reference for further investigations to explore.

Chapter 5

An analysis of the test-retest reliability of the hip extension bench in elite youth soccer players and sub-elite sprinters

5.0 Interlude

Findings from the previous chapter outlined the fundamental requirement of precise hip flexion angle determination upon assessment setup when assessing isometric hip extension strength. Successfully adhering to the recommendations from chapter 4 may increase the usefulness of assessment tools by limiting the measurement error that can arise during assessment. These findings also confirmed the possibility of targeting the hamstrings or G_{max} during assessments of isometric hip extension strength, where positions of hip flexion ($HEB_{70/60}$) may be used to bias the hamstring muscles and positions of hip extension ($HEB_{15/0}$) may be used to target the G_{max} muscle. As such, it seems suitable for the next steps of the project to determine the reliability and subsequent measurement error that may arise from collecting data with the HEB assessment tool at positions that independently bias the hamstrings and G_{max}.

5.1. Introduction

The importance of assessment tool reliability was confirmed within chapter 2 where reproducibility under standardised conditions is vital in order for inferences to be made on the data that is collected. In applied terms, practitioners need to be able to understand when there is a meaningful change in performance in response to an external stimulus, such as a training intervention or period of fixture congestion, for example. This change must be greater than the variation that is expected from a test. This variation may arise from error related to small differences in assessment setup or electronic inconsistencies (random error) or athlete homeostasis, motivation and competence in completing the action of interest (systematic bias). Swinton *et al.* (2018) described that the “true score” of an athlete can never be found within practice, so an “observed score” should be referred to as the product of the “true score” and measurement error of the test. If one was to complete multiple tests on an athlete under the same conditions, the mean of the “observed scores” should be similar to the “true score” and the measurement error would simply define the instrumentation and biological noise (Swinton *et al.*, 2018). Therefore, minimising the measurement error of an assessment tool should be desired so that a close representation of an athlete's "true score" can be collected and more confident decisions can be made.

In chapter 3, several considerations were presented which may cause a threat to successful validity and reliability when not addressed suitably. Some of these considerations were tested in chapter 4 to understand (a) global hip extensor recruitment with the HEB assessment tool (b) the importance of concise determination of limb and joint positioning and (c) the sensitivity of the HEB assessment tool to detect changes in force and muscle activation of the hip extensors upon changing joint angle. At this stage it can be confirmed that the HEB assessment tool is sensitive to changes in joint angle, yet the reproducibility of the tool under standardised conditions is yet to be investigated.

In the past, test-retest investigations have been undertaken on many assessment tools of maximal isometric strength of the lower limbs (Wollin *et al.,* 2016; Opar *et al.,* 2013; Hickey *et al.,* 2017; Kollock *et al.,* 2010; O'Brien *et al.,* 2019). The sample populations used for assessing reliability ranges from recreationally active (Kollock *et al.,* 2010; Hickey *et al.,* 2015) to elite sportsmen and women of specific sports (O'Brien *et al.,* 2019; Wollin *et al.,* 2016) and to a combination of the two (Opar *et al.,* 2013). Generally, as populations hold different physical qualities it can become hard to make inferences on the reliability of a specific cohort and relate it back to your population of interest, in this case soccer players. As such, it may be important to assess the reliability of an assessment tool in specific cohorts prior to implementing values of expected error to one's own population. Additionally, considering the importance of the hip extensor muscles for sprint-acceleration performance, it may be interesting to determine reliability in a cohort of athletes that specialise in such running types. Generally speaking, the reliability of published hip extension assessment tools is good. However, as pointed out in chapter 3's considerations, it may be feasible to have a reliable tool that is not valid. If both reliability and validity considerations are not successfully met, then a reliable tool may simply be reproducing consistent scores of an assessment that is not actually assessing what it claims to be.

As such, it remains that a valid and reliable tool to measure maximal isometric hip extension strength for use within the applied field is currently absent. Additionally, the assessment of reliability in an elite soccer cohort would provide more specific indications of the assessment variability for practitioners within similar fields. Therefore, the primary aim of this chapter is to understand the test-retest reliability of the HEB assessment tool to assess maximal isometric hip extension strength in an elite soccer population.

5.2. Methodology

5.2.1. Participant characteristics

Fifty-two male participants volunteered to take part in the study and were comprised of two separate population samples. One sample represented a population of elite youth soccer players from an English Premier League academy structure (SOC). Within the SOC group, 8 were participating at the U16's level, 15 were at the U18's and 17 were classed as competing at the U23's level. Individuals of each age bracket were grouped as to attain a larger sample size. The second sample represented a population of sub-elite sprinters athletes from a local athletics club (SPR). Inclusion of the SPR group was an addition for the purpose of understanding the reliability of unilateral assessment not previously assessed in the SOC group. Reliability of this cohort was also necessary prior to data collection from the same cohort in chapter 6. All participant characteristics can be found in table 5.1. Athletes in the SPR group were provided with participant information sheets and consent forms to return and a gatekeeper deemed responsible for SOC provided informed consent on behalf of the participating soccer players. Due to the differences in sport participation and level of play, athletes in the SOC and SPR group were kept as two separate groups. The study was approved by the Liverpool John Moores University human research ethics committee which conforms to the ethical standards established by the Declaration of Helsinki.

Table 5.1. Participant characteristics for the SOC and SPR groups (mean ± SD)

Group	Sample size (n)	Age (years)	Height (cm)	Body mass (kg)
SOC	40	17.6 ± 2.1	178.8 ± 7.6	70.4 ± 9.0
SPR	12	23.1 ± 4.7	181.2 ± 6.3	74.4 ± 11.6

5.2.2. Study design

The study was conducted across two locations of an English Premier League teams training grounds in the North West of England and consisted of three separate report days. The first visit included test familiarisation and collection of participant characteristics, whereas the second and third visit comprised of two test days of data collection for test-retest reliability purposes. Each testing session lasted approximately 15 – 25 minutes for each athlete depending on the group and was completed at a similar time of day at a time that suited the corresponding organisation and participating athletes' schedules.

Prior to data collection all athletes undertook a comprehensive familiarisation session completing several MVIC's across 2 to 3 angles. All SOC athletes were deemed somewhat experienced in resistance training (U16's = 1 year; U18's = 1-3 years; U23's = 2-4 years) and had completed HEB assessments previously as part of the corresponding organisations' pre-season assessment battery. The SPR group athletes' resistance training experience was mixed with the majority having no strict previous exposure. Upon assessment days, all athletes were asked to continue their normal nutritional and sleeping habits and refrain from intense exercise within the 48-hour window of assessment. Upon arrival on the day of testing, all athletes completed a comprehensive standardised warm up in accordance with the corresponding organisations' current procedures. This comprised of a 4-minute light exercise on a cycle ergometer, various dynamic stretching and activation exercises and two practice attempts at each position. On both days of testing, participants were required to perform three MVIC's at each HEB position with a minimum of 15 and 90 seconds between repetition and assessment position, respectively. This was also the case for the unilateral assessments for both left and right legs which were randomly ordered into the assessment battery to minimise systematic bias. Assessment setup and MVIC completion was performed in accordance to the recommendations from chapter 3. Verbal encouragement was given throughout the time of assessment and feedback of force data given between repetitions in order to increase motivation. A minimum and maximum of 7 and 14 days was given between familiarisation, test 1 and test 2.

5.2.3. Equipment selection

In order to assess the test-retest reliability of a measure of isometric hip extension strength, the HEB was utilised in accordance to the recommendations from chapter 3. The SOC group completed bilateral only assessments and the SPR group completed both bilateral and unilateral assessments. It was hypothesised that the unilateral assessments would elicit less favourable reliability due to the increased stability demands required during completion of the assessment. For the purpose of test-retest reliability, two positions of hip flexion were assessed for every athlete to represent bilateral and unilateral hamstring (HEB_{60} and UL HEB_{60}) and G_{max} (HEB_{15} and UL HEB_{15}) dominant assessments. These decision to select these angles was made in accordance to the findings from chapter 4 and the preference of the corresponding organisations' practitioners.

5.2.4. Statistical analysis

Descriptive statistics are presented as a mean ± SD for peak force (N) of the participants' maximum of three repetitions and the normality distribution of the data was checked with Shapiro–Wilk analysis. For the unilateral HEB assessments, left and right sides were grouped totalling a sample size of 30 assessments. To assess relative reliability between test 1 and test 2, intra-class correlation coefficients with a two-way mixed absolute agreement model ($ICC_{3,1}$) were utilised in accordance with previous guidelines (Weir, 2005; Koo & Li, 2016). The absolute reliability was determined by calculating the typical error (TE) and coefficient of variation (%TE) (Hopkins, 2000; Hopkins, 2010), minimal difference (MD) was determined as $TE \times 1.96 \times \sqrt{2}$ (Weir, 2005) and expressed as a percentage, and confidence intervals were set at a 95% level (Koo & Li, 2016).

Based on previously published guidelines, an ICC of 0.90 +, 0.80 – 0.89 and 0.79 and below was described as high, moderate and poor, respectively (Vincent, 2005). A %TE of 10% or less was set as the level at which a measure was considered reliable. Finally, in order to account for the dependency of the data i.e. determine the difference between HEB assessment angle (HEB60 vs. HEB15) a one-way ANOVA was performed with subsequent Cohen's D effect size (*ES*) to determine the magnitude of the mean difference ($ES = mean_1 - mean_2$ / pooled standard deviation) . Values of 0.2, 0.5 and 0.8 were deemed as a small, medium and large *ES*. All calculations were performed using SPSS version 26 (SPSS Inc, Chicago, IL, USA) and statistical significance was set at $p < 0.05$ for all calculations.

5.3. Results

5.3.1. Descriptive statistics

The descriptive statistics and pre-analysis normality checks for the two bilateral and unilateral HEB measures can be found in table 5.2. All HEB measures other than UL HEB_{60} were homoscedastic which allowed for analysis without log-transformation. The UL HEB_{60} data was log transformed.

Table 5.2. Descriptive statistics and normality checks for bilateral (SOC & SPR) and unilateral (SPR only) HEB_{60} and HEB_{15} assessments for SOC and SPR groups.

Test Type	**Sample size (n)**	**Mean ± sd (N)**	**Change in the mean (95% CI)**	**Normality of data**
		SOC		
HEB_{60}	40	1763 ± 419	-10 N (-59 to 38)	Homoscedasticity, P = 0.27
HEB_{15}	40	1683 ± 342	8 N (-29 to 44)	Homoscedasticity, P = 0.56
		SPR		
HEB_{60}	12	1744 ± 521	-21 N (-100 to 59)	Homoscedasticity, P = 0.10
HEB_{15}	12	1365 ± 345	-16 N (-60 to 29)	Homoscedasticity, P = 0.61
UL HEB_{60}	12	803 ± 305 N	10 N (-17 to 37)	Heteroscedasticity, P = 0.04
UL HEB_{15}	12	636 ± 214 N	8 N (-28 to 43)	Homoscedasticity, P = 0.12

5.3.2. Reliability coefficients

Table 5.3 presents the absolute and relative reliability results for the two bilateral and unilateral HEB measures. For bilateral conditions, the reliability of the HEB assessment tool in the G_{max} dominant position (HEB_{15}) provided the greatest %TE results, with the hamstring dominant assessment (HEB_{60}) having a higher typical error in both SOC (6.1 vs. 4.8 %) and SPR (6.6 vs. 4.6 %) groups. The unilateral conditions presented marginally and substantially greater %TE scores in comparison to their bilateral counterparts in the

HEB_{60} (7.0 vs. 6.6 %) and HEB_{15} (8.5 vs. 4.6 %) conditions for the SPR group, respectively. Upon closer inspection of MD as a percentage of the mean, the bilateral HEB_{15} (13.1 vs. 12.2 %) and HEB_{60} (16.8 vs. 17.1 %) measures generated similar findings for SOC and SPR groups, respectively. Finally, as hypothesised the MD for the unilateral HEB_{15} (23.5 %) and HEB_{60} (19.1 %) measures were less favourable than the bilateral measures.

Table 5.3. Reliability coefficients for the bilateral and unilateral HEB_{60} and HEB_{15} assessments.

Test Type	ICC (95% CI)	TE (95% CI)	%TE (95% CI)	MD (%)
		SOC		
HEB_{60}	0.95 (0.91 – 0.97)	107 (91 – 132)	6.1 (5.2 – 7.5)	16.8
HEB_{15}	0.95 (0.91 – 0.97)	80 (66 – 103)	4.8 (3.9 – 6.1)	13.1
		SPR		
HEB_{60}	0.97 (0.89 – 0.99)	108 (77 – 183)	6.6 (4.6 – 11.4)	17.1
HEB_{15}	0.98 (0.92 – 0.99)	60 (43 – 103)	4.6 (3.2 – 7.8)	12.2
UL HEB_{60}	0.97 (0.93 – 0.99)	N/A	6.7 (5.1 – 9.5)	18.9
UL HEB_{15}	0.93 (0.85 – 0.97)	53 (41 – 75)	9.8 (7.5 – 14.0)	23.5

5.3.3. HEB_{60} vs. HEB_{15} assessment positions

When observing the two HEB assessment positions, the mean score for the bilateral HEB_{60} (1744 N) was significantly higher ($P < 0.05$) than the HEB_{15} (1365 N) position for the SPR group with a large *ES* (0.86). However, no significant difference ($P = 0.39$) was found for the SOC group (1763 vs. 1683 N) (*ES* = 0.21). The mean score for the unilateral HEB_{60} (803 N) was also significantly higher ($P < 0.05$) than the unilateral HEB_{15} (636 N) position for the SPR group, with a medium *ES* (0.63).

Table 5.4. Mean score differences and ANOVA between HEB measurements angles (HEB_{60} vs HEB_{15}) for SOC and SPR groups

Test Type	Mean ± sd (N)	ANOVA	Age	Participant descriptives
		SOC		
HEB_{60}	1763 ± 419	$P = 0.39$	17.6 ± 2.1	6/8 U16's, 5/15 U18's & 4/17 U23's $HEB_{15} \geq HEB_{60}$
HEB_{15}	1683 ± 342			
		SPR		
HEB_{60}	1744 ± 521	$P < 0.05$	23.1 ± 4.7	2/12 $HEB_{15} \geq HEB_{60}$
HEB_{15}	1365 ± 345			
UL HEB_{60}	803 ± 305 N	$P < 0.05$		
UL HEB_{15}	636 ± 214 N			

5.4. Discussion

To the research group's knowledge, this is the first study to investigate the reliability of a measure of isometric hip extension strength in elite youth soccer players. It is also the first study to utilise load cells with external fixation to measure maximal force production during a supine isometric hip extension setup as opposed to previously assessed prone (Nadler *et al.,* 2000; Scott *et al.,* 2004; Seko *et al.,* 2015; Thorborg *et al.,* 2013), side lying (Meyer *et al.,* 2013), prone-standing (Keep *et al.,* 2016; Lue *et al.,* 2009; Worrell *et al.,* 2001) and standing (Kollock *et al.,* 2010) positions with different types of equipment.

CV values of < 10% and standardised ICC thresholds (0.90 + = high, 0.80 – 0.89 = moderate and < 0.79 = poor) are often utilised to determine the reliability of measures. Therefore, the main findings of the current study are that the HEB assessment tool had high absolute and relative test-retest reliability for measuring bilateral and unilateral maximal isometric hip extension strength across both assessment positions. However, upon observing the TE 95% CI's for the SPR group at HEB_{60} (4.6 – 11.4 %) and UL HEB_{15} (7.5 – 14.0 %) it can be suggested that these acceptable thresholds are not entirely met.

When interpreting the MD value (23.5 %) for the UL HEB_{15} assessment position, an average individual (636 ± 214 N) in this cohort would have to provide an increase of 150

N to their original score for a change to be deemed meaningful. Considering the HEB is a new assessment tool, it is yet to be determined whether a training intervention would provide such increases in performance. However, these values do seem considerably higher than what would be favoured from a practical perspective. As such, it may be suggested that the sensitivity of unilateral measures of maximal isometric hip extension are suboptimal for making inferences about an individual's status within this specific cohort. However, limitations presented further into this discussion may explain possible reasons and solutions for this.

When measuring maximal isometric hip extension strength on the current apparatus (HEB), it is possible to compare test-retest reliability coefficients to previous assessment tools that have utilised different types of equipment. The relative reliability presented in this study are higher than previous assessment types that have utilised isokinetic dynamometry during both dynamic (Julia *et al.,* 2010) and isometric (Keep *et al.,* 2016; Meyer *et al.,* 2013) contractions. Julia *et al.* (2010) reported ICC values of 0.62 – 0.80 for concentric and 0.68 – 0.80 for eccentric contractions, whereas Keep *et al.* (2016) displayed better results of 0.82 (left side) and 0.97 (right side), albeit an intra-session investigation. The utilisation of handheld dynamometry presents varying degrees of reliability success (Scott *et al.,* 2004; Seko *et al.,* 2015) and is substantially influenced by test position (Seko *et al.,* 2015). Seko *et al.* (2015) discovered ICC values of 0.88, 0.80 and 0.76 during seated, prone and standing conditions, respectively. Such differences may arise from the change in direction of force application and limitations surrounding handheld dynamometry, two considerations outlined in chapter 3. Utilising external fixation, Nadler *et al.* (2000) has shown increases in reliability with portable fixed dynamometry (ICC = 0.94, %TE = 7.8%), which seem to be comparable to this study's results. However, Kollock *et al.* (2010) found reduced ICC values of 0.78 with portable fixed dynamometry which are much lower than those found within the present study. This finding can probably be attributed to the poor dynamometer positioning, failing to address the location for acquisition of force consideration from chapter 3. Interestingly, Scott *et al.* (2004) also presented lower inter-session reliability with external fixation (ICC = 0.59) in comparison to handheld dynamometry (ICC = 0.74). It was discussed that this may be due to the participant having an inability to visually see and contract directly against the dynamometer during external fixation in the prone position. Such limitations are not present during handheld dynamometry as the tester positions the dynamometer manually

(Scott *et al.,* 2004). This limitation is also avoided during assessment with the HEB due to its supine nature, as it allows athletes to have increased spatial awareness during assessment. The HEB setup also eliminates the possibility of incorrect/suboptimal application against a dynamometer with the bar attachment and fixings.

As indicated in the introduction, comparing reliability between assessment types can provide useful information on the suitability and usefulness of a tool but it does not take into account the validity of the tools in question. For instance, within chapter 3 various assessment tools to assess isometric hip extension strength were critiqued for their inability to control various considerations related to successful assessment tools. As such, the reliability of the tools that have been compared above may be considered as irrelevant if the tool does not assess what it purports to. Therefore, it may be appropriate to render comparisons to previous measures of hip extension strength as useless. As described in chapter 3, all of the considerations surrounding assessment tool development were addressed during the HEB strength assessment development. In addition, the recruitment of the hip extensors across various hip flexion positions with the HEB setup was successfully explored in chapter 4. As such, it is believed that adherence to chapter 3's considerations and robust findings of chapter 4 deems the HEB a valid measure of maximal isometric hip extension strength.

When comparing between the mean scores for the bilateral and unilateral assessments at HEB_{60} and HEB_{15}, analysis revealed that the SPR groups mean score for bilateral and unilateral HEB_{60} was significantly higher than it was for bilateral and unilateral HEB_{15} ($P < 0.05$). These findings provide similarities to those found in chapter 4 surrounding a decrease in peak force as hip flexion angle decreases. However, this was not the case for the SOC group ($P = 0.385$). Upon inspection, it seems as though these findings may be explained by the overall younger cohort and increased number of younger individuals present within the elite youth SOC group. Six of the 8 U16's (75%) produced similar or greater scores for HEB_{15} in comparison to HEB_{60}, whereas only 5 of the 15 (33%) and 4 of 17 (24%) did for the U18's and U23's, respectively. When looking at SPR, just 2 of 12 (17%) scored similar or greater scores for HEB_{15}, one of which was the youngest of the group. These findings may be partly explained by the reduced maturation of neuromuscular function that can be present in young individuals during long muscle length contractions (Hassani *et al.,* 2009). It has been found that antagonist activation is enhanced in young individuals during isometric training at extreme angles compared to the adult counterparts (Hassani *et al.,* 2009). In addition, it has been suggested that voluntary activation of the agonist is reduced in children when compared to adults (Kanehisa *et al.,* 1995) which could be further accentuated during longer muscle lengths (Kluka *et al.,* 2015).

Limitations

The following limitations present several challenges and drawbacks that come with research in the applied field of professional soccer. One limitation of the data collection procedures in this current study was the inability to control for standardised environmental conditions in the SOC group. For logistical purposes, data collection occurred within the strength and conditioning area of the corresponding organisations training facility. Within this area, distractions from significant others such as teammates and coaches may influence application from the athletes during assessment by means of either reduced task focus or by increasing or reducing motivation to achieve higher scores, for example. Such instances may almost certainly impact upon test systematic bias and the reproducibility of MVIC's in the athletes tested. This is a commonly encountered limitation of work in applied environments and a challenge to practitioners that is rarely discussed in research, but one that may have a large impact on the true validity of MVIC data collection. In regard to the SPR group, such an environment was not so present as data collection occurred with only 2 to 4 individuals present at one time. The individuals of the SPR group were also less familiar with each other so perhaps less likely to influence each other's task application.

A second limitation differentiating the SOC and SPR group surrounds task motivation. Another challenge for practitioners working within the applied field is the ability to achieve "buy-in" from athletes. Within the 40 athletes that made up the SOC group, it must be assumed but is unlikely that each individual sees benefit in assessments that are carried out by sports science and medical departments. As such, it cannot be confirmed with confidence that each individual attempted to provide a true MVIC for each repetition during assessment. As for the SPR group who willingly approached the researchers to participate, this limitation is believed to be not so obvious as they perhaps see more value in the assessment due to a general in-exposure to such assessment tools and feedback availability.

Another limitation of this study was the small sample size and training status of the SPR group. Previous exposure to strength training and testing for the majority of the group was minimal which may suggest that athletes may have required a greater period of time to familiarise to the assessment procedures. This may be especially true for maximal contractions under unilateral conditions where greater stability is required perhaps reducing the opportunity for novice athletes to complete subjective maximal contractions. When looking on an individual level, it seems as though three individuals (athlete "A", "B" and "C") had particularly large changes from test 1 and 2 during the UL HEB_{15} and HEB_{60} (athlete "A" and "C" only) assessments. Considering the small sample size of the cohort, these two individuals may have largely influenced the conclusive reliability scores for the SPR group (see table 5.5). When removing these two individuals from the group, the %TE for unilateral HEB_{60} and HEB_{15} improved to 6.3 and 7.7 % respectively, in comparison to the previous scores of 7.0 and 9.8 %. Therefore, it may be concluded that these individuals would have benefited from a longer period of time for familiarisation.

Table 5.5. Percentage change in peak force across test 1 and 2 during unilateral HEB assessments (mean ± SD)

	Average (%)	**Athlete "A" (%)**	**Athlete "B" (%)**	**Athlete "C" (%)**
UL HEB_{60}	8 ± 5	16	N/A	17
UL HEB_{15}	10 ± 9	32	33	N/A

A final limitation of this study was the lack of standardised conditions that may have been present for a number of individuals in the SPR group. Upon follow up, it arose that a number of the athletes in this group failed to conform to the requests of the research team by taking part in physical activity within 48 h of testing. Completing strength assessments under these conditions may or may not have had a significant impact upon the force generating capacity of the individuals hip extensors due to residual fatigue from the physical activity. This limitation may have also contributed to the reduced reliability coefficients that were found in comparison to the soccer group.

Practical implications and conclusion

The primary aim of this chapter was to investigate the test-retest reliability of the HEB assessment tool to assess maximal isometric hip extension strength in two cohorts; one sample representing an elite youth soccer population and another representing a sub-elite sprinter population. The findings from this study indicate that the HEB was successful in reproducing good reliability under similar conditions in both cohorts, although unilateral measures at HEB_{15} were slightly less successful in producing good reliability (%TE, 9.8). This study also highlights the difficulties that arise when collecting data from both elite and sub-elite cohorts, a topic that is not often discussed in scientific literature but one that may introduce unwanted systematic bias in assessment tools. It is of the research groups belief that the presence of systematic bias will have certainly influenced the quality of data that was collected in the present study. In addition, it is believed that the increased efforts surrounding tool development and validity analysis in chapter 3 and 4 will have certainly minimised the random error that exists in the assessment tool. Because of this, future studies should look to focus closely on ensuring fully standardised conditions are set to enable every chance for successful data collection. Methods of minimising external influences to data collection such as athlete distraction should also be further considered due to the negative influence it may have on the quality of data that is collected.

Chapter 6

An analysis of the relationship between maximal isometric hip extension strength and sprint-acceleration and jump performance in sub-elite sprinters

6.0 Interlude

The purpose of the research team's investigations until now have been to successfully develop a new assessment tool to assess and train isometric hip extension strength. These investigations have been completed through rigorous processes of critiquing current literature, developing a series of considerations required for a new tool to be successful and undertaking continuous refinements of a new assessment tool until all of the before-mentioned considerations were met. Furthermore, investigating the sensitivity of the tool to detect change in muscle and joint behaviour in response to various hip flexion positions and understanding the reliability of the tool under standardised conditions have added to the robust scientific backing of the assessment tool. Now, it seems suitable to do a full circle and revisit the initial purpose of the project to determine the specific importance of hip extension for athletic performance. The novelty of this work lies where a new isometric assessment tool will be used that is perhaps deemed to have increased suitability for the applied environment of professional sport.

6.1. Introduction

The importance of HIE's in soccer was confirmed in chapter 2 and Impelizzeri and Marcora (2009) described such actions as a causal indicator for physical performance and ultimately success in soccer. As such, developing an understanding of an athlete's HIE capacity may be seen as a critical role for sports science practitioners. However, these actions are complex and underpinned by a combination of various physiological and biomechanical variables. One of which is maximal strength, which is widely accepted to be closely related to successful sprint-acceleration and jump performance due to its direct relationship with impulse (Suchomel *et al.*, 2016). As such, increases in lower body strength generally transfer positively to sprint (Seitz *et al.*, 2014) and jump (Harries *et al.*, 2012; Perez-Gomez & Calbet, 2013) performance. Having said this, it is widely accepted that sprint performance is determined by the product of both force and velocity capabilities (Samozino *et al.*, 2016) so is also dependent on the ability of athletes to a) generate high levels of force, b) ensure effective application of force onto the supporting environment and c) produce this force at high velocities (Morin & Samozino, 2016). It can be suggested that success during a jump is underpinned by similar abilities, although it is important to remember that force-velocity relationship of sprinting and jumping are suggested to be distinctly individual (Jiménez-Reyes *et al.,* 2018).

As was discussed in chapter 2, acceleration and velocity is determined primarily by impulse and therefore high levels of force in rapid timeframes. Therefore, assessing the direct relationship between strength/maximum force and sprint-acceleration performance is commonly undertaken in order to (a) understand to what extent strength alone may explain performance during sprint-acceleration (b) estimate sprint-acceleration performance from strength measures and (c) understand how the individual determinants related to strength assessments may underpin sprint-acceleration performance. Investigations surrounding these associations encompass a large pool of sports, assessment types and collection procedures (Suchomel *et al.,* 2016; Harries *et al.*, 2012) and partly because of this, the variability in success of such relationships is large. Associations can be explored by means of simple correlation analysis between an assessment method and an athletic performance measure. For example, one may seek to explain the association between two variables such as 1 RM squat and maximal velocity during a 40 m sprint. When assessing correlation with Pearson's product analysis, a resultant correlation coefficient (r) value will explain the relationship between the two, where thresholds of 0.90 +, 0.70 – 0.89, 0.50 – 0.69, 0.30 – 0.39, 0.10 – 0.29 and < 0.1 indicate relationships that are extremely large, very large, large, moderate, small and trivial, respectively (Hopkins, *et al.*, 2009). Further to this a coefficient of determination (r^2) can also be applied in order to understand the shared variance between the two variables. A limitation of correlation studies is that they provide only a mean of association between two single variables and cannot provide indications of predicting one variable from the other. However, simple linear regression is able to model the relationships and improve understanding of the influential capacity of one variable on another (Swinton *et al.*, 2014). The output of a regression analysis is an equation that can be utilised to predict the dependent variable from one or more independent variables. Doing so may be useful for practitioners in the field when looking to make inferences from their assessment screens and plan effective training interventions based on these variables.

As for the dependent variable, timing gates are frequently utilised to provide measures of speed and time across various sprint-acceleration distances (Cotte *et al.,* 2011; Comfort *et al.,* 2014; Wisløff *et al.,* 2004; Baker & Nance, 1998; Hori *et al.,* 2008; Loturco *et al.,* 2018). Furthermore, advances in technology can now allow for a more comprehensive sprint-acceleration analysis of the kinetic and kinematic determinants of sprint-acceleration performance with use of instruments like non-motorised treadmills (Simperingham *et al.,* 2016). On occasions, EMG may be used in combination with any kinetic and kinematic determinants to provide a measure of physiological muscle activity (Howard *et al.,* 2017). As for jump variables, height and distance in vertical, horizontal and lateral planes are regularly used alongside other force and time derived variables in order to provide several indications on the strategy's athletes employ to maximally jump (Suchomel *et al.,* 2016; Harries *et al.,* 2012).

Alongside collection of the various physiological and biomechanical determinants of sprint-acceleration performance are various concepts surrounding force, velocity and optimal strategies to develop these qualities. The force-velocity relationship was introduced in chapter 2 and describes the maximal rate of skeletal movement and the ability of skeletal muscle to generate force (Cross *et al.,* 2017). This theory has been heavy applied to sprint-acceleration performance in recent years and those that wish to understand the fundamentals are directed towards the comprehensive review by Cross *et al.* (2017).

At this point, it also seems suitable to reintroduce the discussions surrounding the force-velocity theory from the literature review that has become a contentious topic in recent years. The modernised force-velocity theory has been popularised as a means of determining an athlete's force and velocity and subsequently power capabilities. The theory is based upon the original load-velocity theory outlined by A. V. Hill which attempted to explain the relationship between load and velocity within muscle (Hill *et al.,* 1938). The original theory states that as the load imposed on muscle increases, the velocity by which the muscle can contract decreases and readers interested in further understanding this theory are directed to the original literature by Hill *et al.* (1938). To reiterate, the modernised force-velocity theory attempts to translate A. V. Hill's theory to dynamic tasks such as sprint-acceleration (Cross *et al.,* 2017; Samozino *et al.,* 2016), and jumping (Samozino *et al.,* 2008) tasks and methods of calculating force-velocity relationships during these tasks was first introduced by Samozino *et al.* (2010). Since then practitioners have attempted to provide insight into the evaluation of such theories and implications for subsequent training (Morin & Samozino, 2016).. For reasons discussed in the literature review surrounding limitations and flaws of the force-velocity theory, examination of athletes physical capabilities with this theory may be a contentious topic, yet to date it remains the most consistent theory within modern sprint-acceleration related literature (Mendiguchia *et al.*, 2016; Morin & Samozino, 2016; Buchheit *et al.*, 2014; Jiminez-Reyes *et al.*, 2017).

Another theory is the theory surrounding dynamic correspondence (Suarez *et al.*, 2019) which was also outlined in chapter 2. This theory seeks to explain the extent to which an exercise modality may correspond to adaptation of a performance indicator. As a result of the popularity of these theories it is now generally considered that accelerating and sprinting are related skills but hold individual characteristics that separate them from each other, as was detailed in chapter 2. Therefore, it is now believed that training interventions can also shaped to specifically target acceleration or sprint adaptations.

In order to further investigate the relationship between force and velocity during sprint-acceleration performance, radar gun technology has recently been introduced to the field of sports science (Samozino *et al.*, 2016; Cross *et al.*, 2015; Buchheit *et al.*, 2014). Such analysis provides a means of determining a large set of variables which may be used to determine the deficits an athlete may have that limits their ability to further increasing their sprint-acceleration performance. The procedures surrounding radar gun utilisation are comprehensively outlined by Simperingham *et al.* (2019) and encompass three velocity-derived variables; maximal horizonal force at zero velocity (F_0), the theoretical maximal velocity at zero force (V_0) and maximum power output ($P_{\max}$) (Samozino *et al.*, 2016). These variables can in turn provide calculations of instantaneous horizontal force (F_H) and peak power ($P_{\max}$) as well as displacement (m). Notably, the current research group are aware of the critique of these variables, as introduced above surrounding force-velocity vs. load-velocity. However, another critique of this theory may be important to have an awareness of. In the case of maximal velocity at zero force (V_0), during maximum velocity sprinting the amount of force that is exerted to the floor should be minimal. However, it is known that this is not the case (Brughelli *et al.*, 2011; Nagahara *et al.*, 2018; Schache *et al.,* 2014). Instead, it should perhaps be stated that as load increases, greater forces must be exhibited in order to reach the same velocity.

Although the utilisation of radar gun technology may provide key information to practitioners, it is rarely suitable to test an athlete's maximal sprint capacity in an applied setting. This runs especially true in times of demanding training or competition schedules. For these reasons, less strenuous alternatives discussed above may prove an adequate alternative to maximally assessing an athlete's sprint-acceleration ability. However, to the researcher's knowledge there is yet to exist an investigation surrounding the relationship between strength or power assessments and the numerous variables derived from radar gun analysis. Nor has there been any investigations surrounding an isometric measure of hip extension strength and its relatedness to sprint-acceleration and jump performance. As preserving athlete freshness is paramount, understanding how isometric strength of the hip extensors may be associated with radar gun derived sprint-acceleration variables may provide interesting and useful data to practitioners. Therefore, the aim of the present study was to investigate the association between maximal isometric hip extension strength measures with the HEB assessment tool and various force- and velocity-based indicators of sprint-acceleration performance. In light of findings from previous correlational and intervention research studies surrounding hip extension targeted exercise and sprint-acceleration and jump performance, it was hypothesised that isometric hip extension strength would be significantly correlated with sprint-acceleration times over shorter distances and jumping in the horizontal direction. It was also hypothesised that isometric hip extension strength would be most significantly correlated with force-based measures from radar gun technology such as F_0 in comparison to velocity-based measures such as V_0.

6.2. Methods

6.2.1. Participant characteristics

Ten competitive track and field athletes (10 males; age: 22.4 ± 4.3 years; body weight: 74.5 ± 11.2 kg; height: 181.1 ± 5.7 cm) voluntarily participated in the study. The recruitment of sprinters was made due to their specialisation of sprint-acceleration performance and subsequent risk for HSI that comes with the sport, two areas that hip extension may largely support. Prior to participating in the study, athletes were briefed on the experimental design, provided information sheets and signed an informed consent form. The study was performed in accordance with the ethical standards of the Helsinki Declaration and was approved by the Liverpool John Moores University Ethics Committee.

6.2.2. Study design

This cross-sectional descriptive study aimed to examine the relationship and association between isometric hip extension strength measured with the HEB assessment tool and sprint-acceleration and jump performance in competitive track and field athletes. To understand these relationships, participants were required to visit the locations of testing on three separate occasions. Day 1 comprised of sprint-acceleration assessment profiling at Anfield stadium (Liverpool Football Club) and day 2 included a comprehensive familiarisation of the HEB assessment tool protocol outlined in chapter 3 and jump assessment protocols. Day 3 included data collection of the isometric strength and dynamic jump assessments. During this period, participants were instructed to maintain their nutritional and sleep habits and refrain from intense exercise within a 48-h window before each visit. On day 1, a 15 min period was given for athletes to complete a self-selected warm up prior to sprint assessments. After this, participants were then given up to three practice sprint attempts. On day 2 and 3 a standardised warm up was completed comprising of a 4 min of light exercise on a cycle ergometer followed by various dynamic mobility and activation exercises. A 7-day window was kept between each testing day to eliminate the influence of residual fatigue and all assessments were completed at a similar time of day.

6.2.3. Sprint-acceleration assessment procedures

On day 1, a 40 m track with various increments (0, 5, 10, 20, 30 and 40 m) was setup on a grass turf surface to represent the various indicators of performance during maximal acceleration and sprinting. A radar gun (Stalker ATS II, Texas, USA) with a sampling rate of 47 Hz was also setup to provide a means of understanding the inverse linear force-velocity and quadratic power-velocity relationships during sprinting. The radar gun was positioned 10 m directly behind the start line on a tripod set at 1 m above ground to approximately align with the COM of the sprinting participants. Participants were required to start from a stationary standing position with one foot just behind the start line and once participants were in the start position, radar data capture was started. No false step was allowed at the start and participants were instructed to run maximally until through a gate that was positioned 45 m from the start point. Instantaneous horizontal velocity was measured continuously with the radar device, which was connected to a laptop running Stalker ATS System^{TM} software (Version 5.0.2.1, Applied Concepts, Inc., Texas, USA) for data acquisition purposes.

In order to interpret the inverse linear relationship between force and velocity and produce a hyperbolic velocity-time curve the raw acceleration-time data was treated with the following processes as recommended by fellow experts in the field and the Stalker system software guidelines. Unfortunately, to the research team's knowledge, literature within this area on specific recommendations is inexistent. In order to attenuate noise and preserve the data from unwanted artefacts the raw data files were handled by the following procedures. Each trace was then manually analysed in the software system by: (a) removing all data prior to the start and after the finish of each sprint; (b) selecting all trials to be "acceleration runs" thereby forcing the start of the velocity-time curve through the point zero; and, (c) manually removing any extra unexpected high and low data points on the velocity-time curve that are likely caused by movements of the participants' appendicular skeleton. The data was then smoothed with a medium digital filter (fourth order, zero lag Butterworth filter) as recommended by the Stalker handbook guidelines to produce a velocity-time curve with fewer and more realistic fluctuations. Although it is understood that small fluctuations in acceleration are real during maximal acceleration, the step of smoothing of the acceleration-time curve is seen as necessary in the calculations for an estimate of force-velocity relationships. Otherwise, the error associated with each data point will be amplified upon integration to a velocity-time curve. Such instances would result in a greater degree of variation between true data points and a "line of best fit" velocity-time curve that the force-velocity relationship utilises in further estimations. The processed data file for each trial together with the height and body mass of each participant was then imported into a purpose-built force-time analysis software (LabVIEW 2013, National Instruments Corporation Ltd, Newbury, UK) to produce the required force- and velocity-derived sprint-acceleration variables. These rigorous processes were followed for each individual to ensure for consistency across each athlete.

6.2.3.a. Sprint-acceleration assessment inter-tester reliability

Simperingham *et al.* (2019) reviewed the analysis of sprint-acceleration velocity-time curves as measured with the radar gun and outlined the presence of poor-moderate inter-tester reliability. As such, it has been suggested to avoid multiple testers when analysing trials from such assessment tools (Simperingham *et al.*, 2019). Pilot data from the present study of a single trial from each participant confirms these recommendations, especially for variables including a horizontal component or those over shorter distances (table 6.1). Upon observation it seems that movement artefacts are greatest over the first 2 s (see figure 6.1), which is in agreement with previous recommendations (Simperingham *et al.*, 2019) and may explain the greater variation in observer's analysis for variables relating most significantly to these times (F_0, $F_{\text{H Mean}}$, *RF*, 5 m and 10 m). Therefore, the decision was made to analyse all trials by a single observer to avoid the influence of inter-observer variability interfering with possible results.

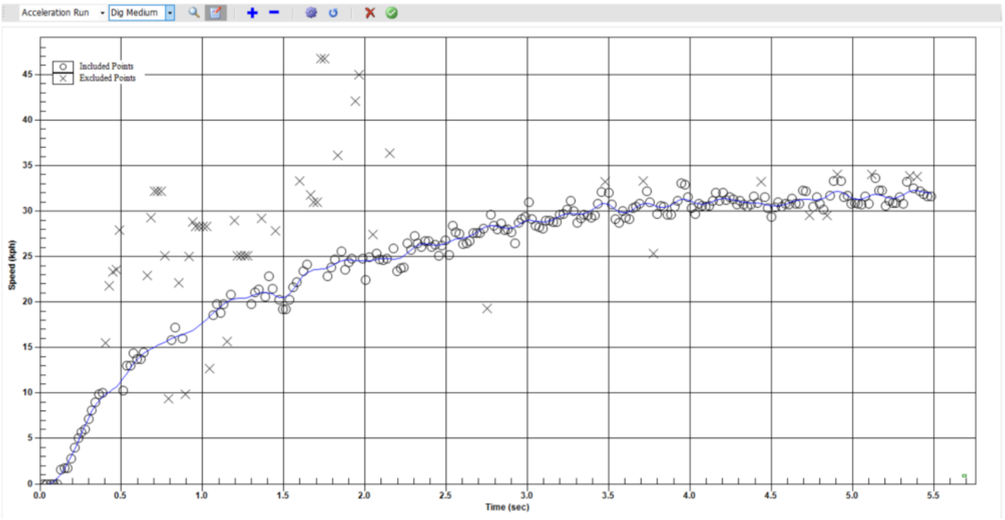

Figure 6.1. A time-cropped force-velocity trace with artefact data points removed and smoothing applied.

Table 6.1. Inter-tester test-retest reliability coefficients for force-, ratio of force- and velocity- derived sprint-acceleration indicators.

Indicator Type	**Average**	**Change in mean**	**ICC**	**TE**	**%TE**	**% MD**
		Force-derived sprint-acceleration indicators				
F_0	497	-158	0.67 (0.37-0.85)	61	12.2	34%
$F_{\text{T Peak}}$	874	-89.8	0.95 (0.88-0.98)	35.5	4.1	11%
$F_{\text{H Mean}}$	499	-1.89	0.68 (0.38-0.85)	60.5	12.3	34%
$P_{\max}$	1109	-287	0.84 (0.66-0.93)	113	10.2	28%
RF_{Peak}	0.47	-0.08	0.43 (0.03-0.71)	0.03	6.3	18%
		Velocity-derived sprint-acceleration indicators				
V_0	9.0 ms^{-1}	0.58	0.91 (0.80-0.96)	0.22	2.4	7%
$V_{\max}$	8.6 ms^{-1}	0.28	0.94 (0.87-0.97)	0.16	1.9	5%

(Thresholds to deem measures reliable are as follows; %TE / CV < 10%, ICC; 0.9 + good, 0.80 – 0.89 moderate, < 0.79 poor. F_0 = theoretical maximum horizontal force, $F_{\text{T Peak}}$ = peak total force, $F_{\text{H Mean}}$ = peak horizontal force, $P_{\max}$ = peak power [W], RF_{Peak} = peak ratio of force [no units], V_0 = theoretical maximum velocity [ms^{-1}] and $V_{\max}$ = maximum velocity. All force-derived units of measurement were N and all velocity-derived units of measurement were ms^{-1} unless otherwise stated).

6.2.3.b. Sprint-acceleration indicator reliability

In an attempt to provide the most useful information within this study and reduce the number of correlations in the analysis process, dependent variable indicators were selected based upon reliability findings from previous literature (Samizino *et al.*, 2016; Simperingham *et al.*, 2019) and the present study (table 6.2). To determine the inter-trial reliability of the sprint-acceleration indicators in the present study, the best two repetitions from each participant was used for subsequent analysis. To assess relative reliability intra-class correlation coefficients with a two-way mixed absolute agreement model ($ICC_{3,1}$) were utilised in accordance with previous guidelines (Weir, 2005; Koo & Li, 2016). The absolute reliability was determined by calculating the typical error (TE) and coefficient of variation (%TE) (Hopkins, 2000; Hopkins, 2010), minimal difference (MD) was determined as TE × 1.96 × √2 (Weir, 2005) and expressed as a percentage, and confidence intervals were set at a 95% level (Koo & Li, 2016). Based on previously published guidelines, an ICC of 0.90 +, 0.80 – 0.89 and 0.79 and below was described as high, moderate and poor, respectively. A %TE of 10% or less was set as the level at which a measure was considered reliable. All calculations were performed using SPSS version 26 (SPSS Inc, Chicago, IL, USA) and statistical significance was set at $p < 0.05$ for all calculations. Indicators deemed to have insufficient reliability have either been removed from the subsequent correlation analysis or are to be taken with caution when interpreting results.

Table 6.2. Inter-trial reliability coefficients for force-, ratio of force- and velocity-derived sprint-acceleration indicators.

Indicator type	**ICC (95% CI)**	**TE (95% CI)**	**% TE**	**MD (%)**
Force based indicators				
F_0	0.93 (0.80 – 0.98)	34.0 (24.9 – 53.6)	5.9 (4.3 – 9.5)	16%
$F_{\text{H Peak}}$	0.81 0.52 – 0.93)	40.0 (29.3 – 63.1)	7.9 (5.7 – 12.7)	22%
$F_{\text{H Mean}}$	0.96 (0.89 – 0.99)	0.22 (0.16 – 0.35)	4.3 (3.1 – 6.9)	12%
$F_{\text{H 2 m}}$	0.94 (0.84 – 0.98)	12.9 (9.46 – 20.4)	4.4 (3.2 – 7.1)	12%
$F_{\text{H 20 m}}$	0.99 (0.98 – 1.00)	0.10 (0.08 – 0.14)	2.0 (1.5 – 2.9)	5%
$F_{\text{H 40 m}}$	0.96 (0.90 – 0.98)	0.23 (0.18 – 0.34)	4.4 (3.3 – 6.4)	12%
$F_{\text{T Peak}}$	0.95 (0.86 – 0.98)	32.9 (24.1 – 51.8)	3.9 (2.8 – 6.2)	11%
$F_{\text{T 2 m}}$	1.00 (0.99 – 1.00)	0.06 (0.04 – 0.09)	1.0 (0.7 – 1.5)	3%
$F_{\text{T 20 m}}$	1.00 (1.00 – 1.00)	0.01 (0.01 – 0.02)	0.2 (0.1 – 0.3)	1%
$F_{\text{T 40 m}}$	1.00 (1.00 – 1.00)	0.75 (0.55 – 1.19)	0.1 (0.1 – 0.2)	0%
$P_{\max}$	0.94 (0.86 – 0.98)	76.8 (60.6 – 115.0)	3.8 (2.8 – 5.8)	11%
Velocity based indicators				
$V_{\max}$	0.93 0.80 – 0.98)	0.19 (0.14 – 0.29)	2.0 (1.5 – 3.2)	6%
V_0	0.98 (0.96 – 0.99)	0.09 (0.07 – 0.13)	1.1 (0.8 – 1.6)	3%
10 m	0.62 (0.03 – 0.89)	0.02 (0.02 – 0.03)	3.3 (2.3 – 6.1)	9%
20 m	0.83 (0.56 – 0.94)	0.07 (0.05 – 0.12)	2.1 (1.6 – 3.4)	6%
30 m	0.90 (0.73 – 0.96)	0.08 (0.06 – 0.13)	1.7 (1.2 – 2.7)	5%
40 m	0.90 (0.73 – 0.96)	0.10 (0.08 – 0.16)	1.7 (1.2 – 2.8)	5%
Ratio of force-based indicators				
S	0.92 (0.78 – 0.97)	4.08 (2.99 – 6.43)	6.4 (4.7 – 10.3)	18%
RF_{Peak}	0.80 (0.50 – 0.93)	0.02 (0.01 – 0.02)	2.9 (2.1 – 4.7)	8%
RF_{Mean}	0.83 (0.56 – 0.94)	0.01 (0.01 – 0.01)	4.9 (3.6 – 7.9)	14%
$RF_{\text{2 m}}$	0.81 (0.52 – 0.93)	0.01 (0.01 – 0.02)	3.5 (2.6 – 5.6)	10%
$RF_{\text{20 m}}$	0.98 (0.96 – 0.99)	0.00 (0.00 – 0.00)	1.4 (1.1 – 2.1)	4%
$RF_{\text{40 m}}$	0.88 (0.68 – 0.96)	0.01 (0.00 – 0.01)	4.3 (3.1 – 6.9)	12%

(F_0 = theoretical maximum horizontal force, $F_{\text{H Peak}}$ = peak horizontal force, $F_{\text{H Mean}}$ = mean horizontal force, $F_{\text{H 2, 20 \& 40 m}}$ = horizontal force at 2, 20 and 40 m, $F_{\text{T Peak}}$ = total force, $F_{\text{T 2, 20 \& 40 m}}$ = total force at 2, 20 & 40 m, $P_{\max}$ = peak power [W], $V_{\max}$ = maximum velocity [ms^{-1}] , V_0 = theoretical maximum velocity, 10, 20, 30 & 40 m = 10 – 40 m sprint times [s], S = slope of the force-velocity relationship, RF_{Peak} = peak ratio of force [no units], RF_{Mean} = mean ratio of force [no units], $RF_{2\text{-}40\text{ m}}$ = ratio of force at 2, 20 & 40 m [no units]. All force-derived units of measurement were N).

6.2.4. Jump assessment procedures

To provide a comprehensive analysis of jump performance, participants completed unilateral and bilateral countermovement jumps in the vertical direction (VCMJ and UL VCMJ) and unilateral countermovement jumps (HCMJ Sum) in the horizontal direction. Countermovement jumps were selected as the measure of vertical and horizontal power as opposed to other jump alternatives for several reasons. Firstly, both vertical and horizontal measures were selected to investigate the theories surrounding movement direction specificity. Secondly, countermovement's were utilised instead of squat jumps due to the fact that almost all athletic movements incorporate at least a slight countermovement. Furthermore, the arm and contralateral leg swing was eliminated to ensure that measures held a truer representation of lower-limb power capabilities, rather than being influenced by the ability to utilise momentum of the non-working limbs. Finally, countermovement jumps encompass a wealth of research in sports science literature so findings from the present study may be comparable to other literature. Vertical countermovement jump performance was measured on an in ground 0.8 x 0.6 m^2 force platform (9287C, Kistler Instruments Ltd., Winterhur, Switzerland) and determined from an impulse-momentum calculation embedded in the corresponding software at a sample rate of 1000 Hz (ForceDecks, ValdPerformance Pty Ltd, Australia). In accordance with Heishman *et al.* (2018), initiation of the downwards phase of the vertical countermovement jumps were detected at a point when the force-time curve dropped below a threshold of 20 N (i.e. 80 kg athlete, threshold is approx. 78 kg). Furthermore, Meylan et al. (2010) utilised a 2.5 % body mass threshold that presents similar values (i.e. 80 kg athlete, threshold is 78 kg). In addition, information from the equipment providers (VALD Performance Pty Ltd, Newstead, Australia) provides further confirmation of these methods as pilot work utilising different thresholds elicits very little influence on the outcome variables, especially when standardised jump procedures are adhered to. For instance, during each vertical jump procedure, athletes in the present study were directed to maintain a still position prior to each jump in order to minimise any disturbances to the estimation of jump height from impulse-momentum calculation. Furthermore, the range of which each jump was to be analysed was manually selected to further reduce the possibility of erroneous fluctuations incorrectly initiating the start of a jumps. Prior to each repetition participants were instructed to keep their hands on their hips and to "dip and drive" by flexing the hips, knees and ankles before performing a triple extension of the lower limbs to jump as high as they could in the upwards direction. Horizontal countermovement jump performance was assessed in accordance to the recommendations from Murtagh *et al.* (2017).

In order to have confidence with the jump assessment dataset, test-retest reliability measures were also carried out where participants were required to revisit the place of testing for a second occasion. During this time, participants were tested under the same conditions and completed the same jump protocol. To determine the test-retest reliability of this data the same procedures were utilised as detailed for the inter-trial sprint-acceleration indicators, above. Information on the test-retest reliability scores can be found below in table 6.3.

Table 6.3. Test-retest reliability coefficients for bilateral and unilateral vertical countermovement jumps and unilateral horizontal countermovement jumps.

Indicator type	**ICC (95% CI)**	**TE (95% CI)**	**% TE**	**MD (%)**
VCMJ	0.91 (0.73 – 0.97)	2.3 (1.7 – 3.8)	5.4 (3.9 – 9.1)	15%
UL VCMJ	0.89 0.77 – 0.95)	2.1 (1.6 – 2.9)	7.3 (5.3 – 12.3)	20%
UL HCMJ Sum	0.94 (0.87 – 0.97)	5.7 (4.5 – 8.1)	3.5 (2.5 – 5.7)	10%

(VCMJ = vertical countermovement jump, UL VCMJ = unilateral vertical countermovement jump, UL HCMJ Sum = the sum of left and right horizontal countermovement jumps. All jump-based units of measurements were cm).

6.2.5. Hip extension strength assessment procedures

The collection of hip extension measures with the HEB strength assessment tool was completed according to the recommendations from chapter 3. To provide a comprehensive battery of hip extension strength assessments, data was collected for both bilateral and unilateral measures of G_{max} (HEB_{15} and UL HEB_{15}) and hamstring (HEB_{60} and UL HEB_{60}) dominant assessments. Although, the research group recommend that findings related to the UL HEB_{15} strength measure are taken with caution due to the less favourable 95 % CI CV findings of reliability in chapter 5. For each assessment three repetitions were completed with a minimum of 15- and 60-seconds recovery given between repetition and assessment position.

6.2.6. Statistical analysis

Data is presented as means ± standard deviations for all HEB and radar gun derived variables. The dependent variables in this study were all sprint-acceleration variables derived from the radar gun and jump platforms and mats. The independent variables were both the bilateral and unilateral G_{max} (HEB_{15}) and hamstring (HEB_{60}) dominant strength. To account for body mass/size, the strength measures were allometrically scaled ($N/kg^{0.67}$) according to Folland *et al.* (2008) when comparisons with velocity-based sprint-acceleration indicators and jump-based indicators were made. It was deemed unsuitable to do so for force-based and ratio of force-based indicators, considering both dependent and independent variables within these comparisons were directly related to the athletes body mass. According to Simperingham *et al.* (2019)'s recommendations, sprint variables that included a force component or existed within the first 10 m of acceleration were averaged across the best two trials for each participant. The highest/quickest score over the three sprints for all other radar gun derived variables was used for analysis. Upon analysis, performed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA), normality of the data was tested using the Shapiro-Wilk test. Pearson product-moment coefficient of correlation's (r) were then used to determine the relationships between the independent and dependent variables described above. The threshold used to qualitatively assess the correlations was based on the following criteria:

<0.1, trivial; 0.1–0.29, small; 0.3–0.49, moderate; 0.5–0.69, large; 0.7–0.89, very large; >0.9 nearly perfect (Hopkins et al., 2010). The level of significance was set at $P < 0.05$. To further investigate the predictive ability of the independent variables on the dependent variables, a stepwise simple linear regression was applied to all relationships that reached significance. Total variance was reported by the coefficient of determination (r^2) and the respective level of significance (P value). In addition, parameter estimate (B), SE, standardized estimates (b coefficients), and t values were also described.

6.3. Results

6.3.1. Descriptive statistics

Table 6.4 presents the descriptive statistics of the hip extension strength, sprint-acceleration and jump based data for the participants. Measures of isometric hip extension were significantly higher for both bilateral and unilateral measures at HEB$_{60}$ when compared to HEB$_{15}$.

Table 6.4. Descriptive data of the sprint athletes' performances in the HEB and sprint assessments.

Hip extension strength indicators (absolute [N])

HEB$_{60}$	HEB$_{15}$	UL HEB$_{60}$	UL HEB$_{15}$
1654±465	1334±379	813±288	667±198

Force-based sprint-acceleration indicators (N)

F_0	$F_{\text{T Peak}}$	$F_{\text{T 2 m}}$	$F_{\text{T 20 m}}$	$F_{\text{T 40 m}}$	$F_{\text{H Mean}}$	$F_{\text{H 2 m}}$	$F_{\text{H 20 m}}$	$F_{\text{H 40 m}}$	$P_{\max}$
488	881	787	752	744	127	289	152	110	1141
± 86.0	± 133	± 119	± 113	± 111	± 21.1	± 49.8	± 25.9	± 18.7	± 224

Velocity-based sprint-acceleration indicators

V_0	$V_{\max}$	10 m	20 m	40 m
9.76±0.60 ms^{-1}	9.26 ± 0.54 ms^{-1}	2.23 ± 0.10 s	3.44 ± 0.15 s	5.69 ± 0.25 s

Ratio of force-based sprint-acceleration indicators

S	RF_{Peak}	$RF_{\text{2 m}}$	$RF_{\text{20 m}}$	$RF_{\text{40 m}}$
-47.3 ± 7.69	0.47 ± 0.03	365 ± 0.02	0.20 ± 0.02	0.15 ± 0.01

Jump-based indicators (cm)

VCMJ	UL VCMJ	UL HCMJ Sum
43.8 ± 5.96	23.9 ± 5.22	352 ± 39.5

(F_0 = theoretical maximum horizontal force, $F_{\text{H Peak}}$ = peak horizontal force, $F_{\text{H Mean}}$ = mean horizontal force, $F_{\text{H 2, 20 \& 40 m}}$ = horizontal force at 2, 20 and 40 m, $F_{\text{T Peak}}$ = total force, $F_{\text{T 2, 20 \& 40 m}}$ = total force at 2, 20 & 40 m, $P_{\max}$ = peak power [W], $V_{\max}$ = maximum velocity [ms^{-1}] , V_0 = theoretical maximum velocity, 10, 20, 30 & 40 m = 10 – 40 m sprint times [s], S = slope of the force-velocity relationship, RF_{Peak} = peak ratio of force [no units], RF_{Mean} = mean ratio of force [no units], $RF_{\text{2-40 m}}$ = ratio of force at 2, 20 & 40 m [no units], VCMJ = vertical countermovement jump, UL VCMJ = unilateral vertical countermovement jump, UL HCMJ Sum = the sum of left and right horizontal countermovement jumps. All force-derived units of measurement were N and all jump-based units of measurements were cm).

6.3.2. Pearson's correlation coefficients

Table 6.5 represent the correlation coefficients (r) values for the relationship between absolute and relative HEB scores and force- and velocity-based sprint-acceleration scores and jump scores, respectively. The largest correlation values between HEB measures and force-based sprint-acceleration variables were obtained for the HEB_{60} assessment with F_0 (r = 0.802, P < 0.01), For the velocity-based sprint-acceleration variables, no isometric hip extension strength measure were significantly correlated, with the closest to significance being $HEB_{60\ rel}$ with 20 m time (r = -0.545, P = 0.103). There was also no significant correlation between isometric hip extension strength measures and any ratio of force-based indicators of sprint performance. The closest to significance here was S and $HEB_{60\ rel}$ (r = -0.601, P = 0.066). The only correlation between the isometric hip extension strength and jump variables was found between UL $HEB_{60\ rel}$ and UL HCMJ Sum (r = 0.688, P < 0.028).

Table 6.5. Correlation coefficients (r) between various absolute (force-based, ratio of force and jump-based) and allometrically scaled (velocity-based only) HEB measures with indicators of sprint-acceleration and jump performance

Force-based sprint-acceleration indicators

Indicator Type	HEB_{60}	HEB_{15}	UL HEB_{60}	UL HEB_{15}
F_0	0.802^{**}	0.698^{*}	0.608	0.513
$F_{T\ Peak}$	0.742^{*}	0.776^{**}	0.568	0.471
$F_{T\ 2\ m}$	0.687^{*}	0.768^{**}	0.529	0.431
$F_{T\ 20\ m}$	0.666^{*}	0.764^{*}	0.513	0.419
$F_{T\ 40\ m}$	0.662^{*}	0.763^{*}	0.509	0.416
$F_{H\ Mean}$	0.629	0.636^{*}	0.518	0.388
$F_{H\ 2\ m}$	0.779^{**}	0.723^{*}	0.610	0.481
$F_{H\ 20\ m}$	0.676^{*}	0.694^{*}	0.563	0.426
$F_{H\ 40\ m}$	0.616	0.630	0.523	0.380
P_{max}	0.752^{*}	0.651^{*}	0.603	0.476
Velocity-based sprint-acceleration indicators				
V_0	0.118	0.077	0.190	0.075
V_{max}	0.081	0.046	0.174	0.065
10 m	-0.319	-0.166	-0.320	-0.283
20 m	-0.545	-0.308	-0.481	-0.395
40 m	-0.479	-0.194	-0.311	-0.280
Ratio of force-based sprint-acceleration indicators				
S	-0.601	-0.560	-0.348	-0.275
RF_{Peak}	0.396	0.147	0.292	0.282
$RF_{2\ m}$	0.425	0.178	0.349	0.302
$RF_{20\ m}$	0.113	0.016	0.166	0.107
$RF_{40\ m}$	0.041	-0.050	0.134	0.015
Jump-based indicators (cm)				
VCMJ	0.135	-0.049	0.150	0.021
UL VCMJ	-0.141	0.048	-0.059	0.096
UL HCMJ Sum	0.502	0.439	0.688^{*}	0.568

(** and * indicate significance of $P < 0.01$ and $P < 0.05$, respectively. No asterix implies no significance. F_0 = theoretical maximum horizontal force, $F_{H\ Peak}$ = peak horizontal force, $F_{H\ Mean}$ = mean horizontal force, $F_{H\ 2,\ 20\ \&\ 40\ m}$ = horizontal force at 2, 20 and 40 m, $F_{T\ Peak}$ = total force, $F_{T\ 2,\ 20\ \&\ 40\ m}$ = total force at 2, 20 & 40 m, P_{max} = peak power [W],

V_{max} = maximum velocity [ms^{-1}] , V_0 = theoretical maximum velocity, 10, 20, 30 & 40 m = 10 – 40 m sprint times [s], S = slope of the force-velocity relationship, RF_{Peak} = peak ratio of force [no units], RF_{Mean} = mean ratio of force [no units], $RF_{2\text{-}40\ m}$ = ratio of force at 2, 20 & 40 m [no units], VCMJ = vertical countermovement jump, UL VCMJ = unilateral vertical countermovement jump, UL HCMJ Sum = the sum of left and right horizontal countermovement jumps. All force-derived units of measurement were N and all jump-based units of measurements were cm).

6.3.3. Linear regression

Simple linear regression equations were calculated to predict dependent variables from the independent variable that held greatest significance according to the correlation analysis in table 6.5 (see table 6.6 and figure 6.2). Results from this analysis can be utilised to generate predictions equations for the dependent variable of interest, for example:

> "A simple linear regression was calculated to predict F_0 based on HEB_{60} values. A significant regression equation was found ($F_{(1,9)} = 14.46$, $P < 0.01$) with an r^2 of 0.644 and the participants predicted F_0 is equal to 242.42 + 0.148*HEB_{60} N. The sprint athletes improved F_0 by 0.148 N for each 100 N of HEB_{60}."

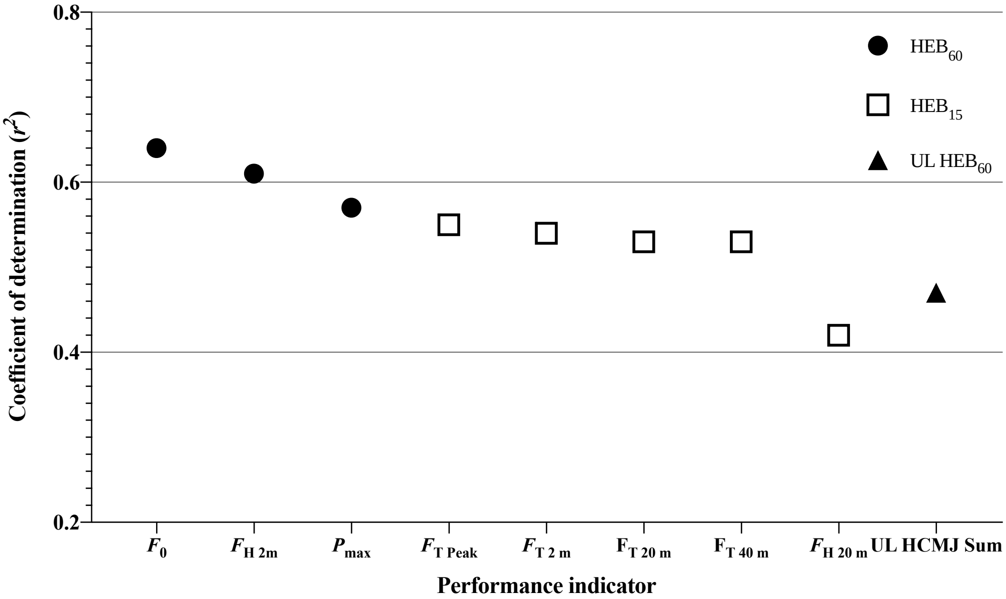

Figure 6.2. Coefficient of determination (r^2) for the sprint-acceleration and jump performance indicators included in the linear regression analysis.

Table 6.6. Results of simple regression analysis between significantly correlated HEB measures and sprint-acceleration or jump performance indicators.

Variable	Predictor	*B*	*SE*	Stand. Est.	*t*	P	r^2
Force-based sprint-acceleration indicators							
F_0	HEB$_{60}$	0.15	0.04	0.80	3.80	< 0.01	0.64
$F_{\mathrm{H\ 2m}}$	HEB$_{60}$	0.08	0.02	0.78	3.52	< 0.01	0.61
P_{max}	HEB$_{60}$	0.36	0.11	0.75	3.23	= 0.01	0.57
$F_{\mathrm{T\ Peak}}$	HEB$_{15}$	0.27	0.08	0.78	3.48	< 0.01	0.55
$F_{\mathrm{T\ 2\ m}}$	HEB$_{15}$	0.24	0.07	0.77	3.39	= 0.01	0.54
$F_{\mathrm{T\ 20\ m}}$	HEB$_{15}$	0.23	0.07	0.76	3.35	= 0.01	0.53
$F_{\mathrm{T\ 40\ m}}$	HEB$_{15}$	0.22	0.07	0.76	3.34	= 0.01	0.53
$F_{\mathrm{H\ 20\ m}}$	HEB$_{15}$	0.05	0.02	0.69	2.73	= 0.03	0.42
Jump-based indicators							
UL HCMJ Sum	UL HEB$_{60}$	1.95	0.73	0.69	2.68	= 0.03	0.47

(significance threshold set at $P < 0.05$. (F_0 = theoretical maximum horizontal force, $F_{\mathrm{H\ Peak}}$ = peak horizontal force, $F_{\mathrm{H\ Mean}}$ = mean horizontal force, $F_{\mathrm{H\ 2\ \&\ 20\ m}}$ = horizontal force at 2 & 20 m, P_{max} = peak power [W], $F_{\mathrm{T\ Peak}}$ = total force, $F_{\mathrm{T\ 2,\ 20\ \&\ 40\ m}}$ = total force at 2, 20 & 40 m, UL HCMJ Sum = the sum of left and right horizontal countermovement jumps. All force-derived units of measurement were N and all jump-based units of measurements were cm).

6.4. Discussion

The aim of the present study was to investigate the relationship between an isometric measure of maximal hip extension strength and sprint-acceleration and jump performance in a cohort of competitive sprinters. It was hypothesised that hip extension strength capacity would be significantly associated with several indicators of sprint-acceleration and jump performance. Secondly, it was believed that performance indicators more specifically related to force and horizontal directions would present a higher correlation with hip extension measures. Generally, the main findings of the present study are in agreement with the hypothesised results, where measures of bilateral hip extension strength were most significantly correlated with performance indicators of sprint-acceleration and jump performance that favoured force and direction in the horizontal plane. These findings were significant for both hip extension strength in the hip flexed position (HEB_{60}) and the hip extended position (HEB_{15}). Of these findings, F_0 was the most highly correlated force-based indicator with HEB_{60} ($r = 0.80$) and $F_{T\ Peak}$ was the most highly correlated force-based indicator to HEB_{15} ($r = 0.78$). Secondly, HCMJ Sum was the only jump-based indicator of performance to correlated with maximal isometric hip extension strength, UL HEB_{60} ($r = 0.69$). In contrast, there was a lack of significant associations between hip extension strength measures and both velocity-based and ratio of force-based indicators of sprint-acceleration performance. The velocity-based and ratio of force-based indicators that were closest to reaching significance was 20 m sprint time ($r = -0.545$, $P = 0.103$) and S ($r = -0.601$, $P = 0.066$) when correlated to $HEB_{60\ rel}$, respectively.

To the authors' knowledge, this is the first study to investigate the relationship between strength assessments and radar gun derived force and velocity indicators of performance. Considering the novelty of the independent and dependent variables, comparing results to previous investigations presents some difficulty. Ideally, results would be compared with previous literature utilising similar modalities, yet there is a significant inexistence of such data. As such, previous investigations utilising the most similar measures of strength, sprint-acceleration and jump data are included for comparative purposes.

The only previous investigation to assess the association between hip extension capacity and force-based sprint-acceleration variables is from Morin *et al.* (2015). Horizontal GRF assessed via an instrumented treadmill (Morin *et al.*, 2010) was highest in individuals that had both the highest torque production of the hip extensions, assessed via isokinetic dynamometry and the highest hamstring activity during end-of-swing (Morin *et al.*, 2015). In addition, a previous investigation associating mean propulsive power during a barbell hip thrust with sprint-acceleration performance found very large ($r = 0.85$) to nearly perfect ($r = 0.95$) relationships with sprint distances from 10 to 150 m (Loturco *et al.*, 2018). These findings are considerably higher than those found in the present study. Investigations utilising other assessment types such as the back squat also demonstrate very ($r = 0.71$) and extremely large ($r = 0.94$) associations with 30 and 10 m sprint-acceleration performance (Wisløff *et al.*, 2004). In addition, Cotte *et al.* (2011) presented similar findings under isokinetic knee extensor contractions at 180, 240 and 300 °/s ($r =$

0.77, 0.74 and 0.80, respectively) for average velocity over 20 – 30 m sprint-acceleration trials. Over a shorter distance, Comfort *et al.* (2014) discovered estimated 1 RM back squat absolute measures to inversely correlate with 5 m sprint times (r = -0.52 to -0.67). Generally, the correlations presented here seem to be slightly higher than those found in the present study. However as previously indicated, direct comparisons become hard to make due to the difference in assessment selection, contraction modality and dependent variable assessment tool. The isometric and isolated nature of the HEB strength assessment ensures specific isolation of the hip extensor muscles under conditions of increased stability, whereas a 1 RM for example incorporates muscles across the lower and upper limbs. In addition, the dynamic nature of a squatting task perhaps requires greater coordination and successful execution may be influenced by other factors such as contraction and movement velocity. As such, it cannot be said whether voluntary strength alone explains the correlation between dynamic measures of strength and sprint-acceleration performance – a limitation of previous investigations.

Force-based indicators

The most significant correlations presented in this chapter were those associated with force, power and especially those relating to horizontal forces (F_0, $F_{\mathrm{T\ Peak}}$, $F_{\mathrm{T\ 2\text{-}40\ m}}$, $F_{\mathrm{H\ Mean}}$, $F_{\mathrm{H\ 2\text{-}20\ m}}$, $P_{\max}$). Information provided in chapter 2 surrounding the kinetics and kinematics of sprint-acceleration performance can be used to explain some of the findings in the present study. For instance, the muscle and joint requirement of hip extension for sprint-acceleration performance has been confirmed in the past through measures of EMG (Higashihara *et al.,* 2017) and studies outlining movement kinematics during sprint-acceleration performance (Bartlett *et al.,* 2013; Buchheit *et al.,* 2014; Dorn *et al.,* 2012; Morin *et al.,* 2015; Schache *et al.,* 2014). Furthermore, the importance of muscle strength and maximal force application (Stone *et al.,* 2002; Suchomel *et al.,* 2016) during sprint-acceleration has also been confirmed. More specifically, substantial evidence exists to suggest the importance of horizontally oriented force for successful sprint-acceleration performance (Hunter *et al.,* 2005; Brughelli *et al.,* 2011; Morin *et al.,* 2011; 2012; Loturco *et al.,* 2015; Nagahara *et al.,* 2018). This is perhaps partly due to the longer GCT's observed during acceleration that provide increased time for concentric hip extension force application (Dorn *et al.,* 2012). Finally, the acceleration phase of sprint-acceleration also requires a greater forward lean of the trunk which may place greater emphasis on the hip extensors to provide force accentuation throughout the full range hip extension. For these reasons, various recommendations point towards hip extension training for sprint-acceleration performance over shorter distances (Morin *et al.,* 2015; Contreras *et al.,* 2016; Brown *et al.,* 2017; Abade *et al.,* 2019; González-García *et al.,* 2019) such as those investigated in the present study.

Velocity-based indicators

In the present study, no significant correlations existed for maximal isometric hip extension strength measures across all distances measured with the radar gun. Strength measurements collected with hip flexion (HEB_{60}) when compared to hip extension (HEB_{15}) presented slightly greater associations with sprint times and indicators representative of maximum velocity yet remained insignificant. Velocity-based findings in the present study can be explained by previous literature outlined in chapter 2 surrounding the physiology and biomechanics of maximum velocity running. In contrast to maximal acceleration, it is generally believed that maximum velocity sprinting is determined by greater vertical GRF (Weyand *et al*., 2000; Morin *et al*., 2011), increased lower limb stiffness (Wild *et al.,* 2015) and hip extensors activity in the vertical plane (Weyand *et al.,* 2010. As such, it can be suggested that horizontal force seems to be of slightly lesser importance. Buchheit *et al.* (2014) confirms this through findings of 10 m split times having no significant interaction with F_0 in highly trained soccer players. These findings may also be partly due to the shorter GCT's that are present during maximum velocity running (Wild *et al.,* 2015), causing a shorter period of time for additional forwards propulsion to be applied, thereby limiting hip extensor activity. As such, less apparent correlations between hip extension strength and maximum velocity variables may be expected.

Jump performance

Regarding the relationship between isometric hip extension strength and jump performance, UL $HEB_{60\ rel}$ measures were associated with horizontal jump performance ($r = 0.69$) but no correlations were found between any HEB measures with vertical jump measures. Considering the horizontal jump actions were performed unilaterally, correlations between unilateral HEB measures and not bilateral may be expected. Additionally, these findings again correspond to the theories of dynamic correspondence and force-vectors, due to the horizontal jump and HEB measures holding similarities in respect to facets of each movement. During vertical jumping, joint torque of the hip extensors just prior to leaving the ground must be at or near-zero to ensure vertical displacement of the centre of mass (Dobbs *et al.,* 2015). As is with the squat exercise, an accentuated region of activity of the hip extensors is at a position of deep hip flexion. In opposition, joint torque is suggested to be high just before take-off in order to propel the centre of mass forwards during horizontal jumping, where an accentuated region of force production may be found (Dobbs *et al.,* 2015; Murtagh *et al.,* 2017). This can be confirmed via EMG investigations of high activity during this period (Murtagh *et al.,* 2017). Furthermore, it seems as though the hip extensors are heavily required throughout the whole phase of a horizontal jump where they are initially eccentrically loaded prior to a forceful concentric and propulsive action (Murtagh *et al.,* 2017). For these reasons, it is postulated that the several shared facets of the HEB assessment tool and horizontal jump technique largely explain the closer relationship between these variables.

Limitations

A limitation of the present study is the potential inconsistencies that arise from assessment tools to assess sprint-acceleration performance. The importance of maintaining reliability for sprint-acceleration measures is outlined by Simperingham *et al.* (2016) in order to be able to identify small but practically important changes in performance over time. Simperingham *et al.* (2019) also suggested that radar gun derived variables that represent information within the first 10 m of acceleration or with a horizontal component present relatively weaker reliability. Therefore, difficulty may be added when comparing results from one assessment tool to those from another. Additionally, it is recommended for results that represent early acceleration and horizontal force to be taken with caution due to the possibility of limitations that are present. With that being said, all trials of this nature were averaged across two trials rather than a maximum value taken in an attempt to increase the reliability and validity of the data (Simperingham *et al.,* 2019).

A second limitation is the method surrounding data handling in the radar gun analysis software. There is yet to exist a strict set of standardised guidelines for the analysis process after subsequent data collection. Therefore, throughout the data handling process, educated decisions surrounding data clipping, smoothing and removal of artefacts were made based on previous literature (Simperingham *et al.,* 2019) and conversations with the research team and experts in the field. In addition, it is understood that the decision to excessively smooth fluctuations in acceleration-time data points somewhat dampens the “realistic” nature of the data. Such processes are believed to be required for estimations of the force-velocity relationship theory, yet the impact of this on the validity of this relationship is unknown and literature within this area is again largely unknown. Therefore, it cannot be confirmed that the data would present exactly the same findings when analysed with slightly different instructions or that the force-velocity relationship determined by the calculations in the field are totally representative of the targeted physical ability in athletic performance.

Jump assessments within this study were utilised to represent a proxy measure of lower limb power in the vertical and horizontal direction. This presents as a limitation to the study considering the recently presented limitations surrounding vertical jump height as an indicator of vertical power (Morin *et al.*, 2019). When utilising CMJ height to describe power capacity, issues arise surrounding inter-athlete push-off distance, optimal loading and force-velocity profile differences exist (Morin *et al.*, 2019). Additionally, surrounding individual differences in jump strategy have also been suggested to influence the force-time characteristics of a jump, and consequently, jump height (Chavda *et al.*, 2017). As such, a reflection of this study and suggestions for future investigations would be to investigate more appropriate variables to represent power capacity during a jump. One such method would be through direct computation utilising body mass, gravitational acceleration, vertical push-off distance and jump height, as detailed in Samozino *et al.* (2008). Finally, although measures were put in place to minimise the risk, decreased stability present prior to initiation of the UL VCMJ may have increased the potential of noise interfering with the jump initiation threshold.

A final limitation was the small size and specificity of the cohort that was recruited for the study. Due to the constraints of professional football, it was not feasible to access this type of athlete for the present study. Unfortunately, this meant that it was necessary to look outside of the collaborating organisations population for participants. In an attempt to maintain a strong competitive level and relevant population to the task in hand, competitive sprinters were recruited. As such, it cannot be said if a larger and slightly different population of individuals would present findings similar to those found within the present study. Therefore, the research team would recommend that caution is taken when applying results from this study to other populations and would urge practitioners to attempt to replicate similar methodologies from the present study in their own population.

Practical implications and conclusion

From a practical perspective, the strong correlations documented with force-based indicators herein may encourage practitioners to assess their athletes frequently through the simple and safe use of isometric hip extension strength measures. This may be especially useful during the heavy training and competition schedules in soccer, when avoiding "real" speed assessments is understandable due to the increased risk of eliciting neuromuscular fatigue or subsequent injury. In addition, in line with previous research (Seitz *et al.,* 2014), the results of this study illustrate the importance of developing high levels of strength to enhance sprint-acceleration performance. More specifically, it can be confirmed that hip extension strength exists as an important determinant of sprint-acceleration performance in competitive sprint athletes. The correlations also somewhat agree with previous literature recommending hip extension exercise for acceleration performance and the facets surrounding the theories of dynamic correspondence and force-vectors. To reiterate, the HEB assessment requires participants to apply force in an anteroposterior horizontal direction relative to the body. Force expression for the hip extensors with the HEB assessment tool is also accentuated at positions of longer lengths (HEB_{60}) and near full hip extension (HEB_{15}). A combination of these facets may partly explain the correlations exhibited in this study due to their similarity to facets that are experienced during sprinting and horizontal jumping.

Finally, the varied associations presented in this study remind the reader of the wider picture that is athletic performance. Large correlations were found between the HEB strength assessments and force-based variables and no significant correlations were found when compared to velocity-based variables. In both circumstances, the complex and multifactorial nature of sprint-acceleration performance is not to be forgotten, such as joint stiffness on ground contact, stride length and frequency, rate of force development and other muscle group contribution. Therefore, it would be ill-advised to recommend a sole focus of hip extension training for force-based results and ignorance of hip extension training for velocity-based results. Instead, an integrated combination of strength, power, technique and energy system development is required in order to achieve successful adaptations in the complex skill of sprint-acceleration performance.

Chapter 7

Synthesis

7.0. Interlude

The intention of this chapter is to provide a conceptual interpretation of the findings from each chapter in respect to the original aims and objectives of the thesis. After a discussion surrounding the successful achievement of the aims and objectives, practical recommendations around future application of the HEB assessment tool and hip extension directed training will be provided. Such recommendations are made to aid practitioners within the field to apply the new techniques to assess and train isometric hip extension strength if seen necessary, as a consequence of the present research findings. In addition, the real-world application of training and assessment tools will be discussed where both advantages and disadvantages exist from an applied and research perspective. Finally, recommendations for future research and potential avenues worth exploring will conclude the chapter.

7.1. Achievement of aims and objectives

The aim of the thesis was to maximal hip extension strength in professional soccer with respect to assessment and physical performance. This aim was achieved by the successful completion of four objectives.

7.1.1. **Objective 1.** To determine the specific role of hip extension in professional soccer and critique the current tools available to assess hip extension strength, with a view of rationalising the development of a novel tool.

Within the literature review objective 1 was explored by critiquing the literature currently available surrounding injuries (2.2) and physical performance (2.3) in soccer and for maximal strength assessments in sport (2.4). It seems apparent that hip extension is becoming a capacity of great interest when determining an athlete’s susceptibility to sustaining HSI and within the prevention of knee ligament injuries in soccer. It was also concluded that hip extension plays an essential role in the performance of high intensity efforts such as sprint-acceleration, change of direction and jumping, all vital actions in the sport of professional soccer. This evidence comes from both kinetic and kinematic analysis investigations on a series of populations. The final section of the literature review introduced strength assessments as a relevant topic when the investigation of hip extension was to be made. A critique of current types of strength assessments was made where factors such as generality vs. specificity and environmental constraints can the suitability of an assessment tool for use. Finally, a rationale for the requirement of a new isometric hip extension strength assessment tool was provided, to conclude a reasoning for the succeeding chapters.

7.1.2. **Objective 2.** To develop a novel tool to assess isometric hip extension strength (hip extension bench, HEB) that successfully meets a framework of considerations required for the development of such tools.

Objective 2 was addressed in chapter 3. Section 3.1. introduced a framework of considerations that were deemed as essential to adhere to upon the development and application of a successful isometric hip extension strength assessment tool. It was introduced that various considerations but general and specific towards hip extension exist that require close attention when developing a new tool to assess hip extension strength. When adhered to correctly, each of these considerations were suggested to have a direct influence on the validity and reliability of an assessment tool and its appropriateness for integration into a battery of assessments. As such, the suitability of current assessment tools at the time were critiqued in respect to each consideration and rationale for the requirement of a novel assessment tool was developed.

In order to meet these requirements, section 3.2. introduced a narrative of events that outlined the developmental timeline of the HEB assessment tool. Throughout this text, indications of where previous versions of the assessment tool successfully met and failed to adhere to the framework of considerations presented in 3.1. were provided in table format. Section 3.2. then concluded with the presentation of the final HEB assessment tool and a table of information outlining how each of the considerations in the framework had been successfully adhered to. At this stage, it was indicated that successful adherence to these considerations would support the notion of a valid and reliable tool, where the minimisation of random error would be achieved, a factor that strongly contributes towards measurement error.

The final section of chapter 3 provided comprehensive information surrounding utilisation and application of the HEB assessment tool. The selection of equipment was presented and procedures surrounding assessment setup and guidelines for data collection were given. This information was given to present methodological transparency and indicate the level of detail and accuracy that the research team believe is required when developing new strength assessment tools. Information in this section can also be used by practitioners as a means of implementing the assessment tool with clear standardised methods of data collection, to further minimise the possibility of random error acquisition.

7.1.3. **Objective 3.** To investigate the sensitivity of the HEB assessment tool to detect change in muscle activity and force production in response to changes in hip flexion angle.

Chapter 4 successfully met the third objective of the project by comparing force and muscle activity during isometric hip extension at various hip flexion angles. Findings confirmed previous research that increasing hip flexion results in a significant linear increase in force production of the hip extensors under isometric conditions. It was also confirmed that as hip flexion increased, peak G_{max} muscle activity reduced and BF_{lh} and ST muscle activity increased. These findings were most significant at the most outer range positions ($HEB_{70/60}$ vs $HEB_{0/15}$). Several reasons can be discussed to explain these changes in neuromuscular function although the exact mechanisms may still not be totally confirmed.

From an applied perspective the successful completion of this objective can have implications for practitioners to be selective with specific joint angles when measuring and training the hip extensor muscle group. The results also prompt practitioners to be precise with their setup procedures in order to ensure stable and standardised conditions.

7.1.4. **Objective 4.** To investigate the test-retest reliability of the HEB assessment tool across two different bilateral and unilateral hip flexion angles.

The completion of chapter 5 addressed objective 4 by the following. After subsequent analysis of the sensitivity of the HEB assessment tool, two assessment positions were chosen to determine test-retest reliability (HEB_{60} and HEB_{15}). These positions were chosen as a consequence of the findings from chapter 4 that presented a distinct targeting of the hamstring muscles and G_{max} muscle in positions of hip flexion (HEB_{60}) and hip extension (HEB_{15}), respectively. The decision-making process for the selection of these positions was partly governed by certain environmental circumstances, as outlined in chapter 5.

In order to understand the reliability of the assessment tool under standardised conditions, 40 elite youth soccer (SOC) and 15 competitive sprint (SPR) athletes were assessed on two occasions. The results obtained in chapter 5 generally provided indications of good reliability for bilateral and unilateral assessments, yet HEB_{60} (4.6 – 11.4 %) and UL HEB_{15} (7.5 – 14.0 %) held CV 95 % CI's that are just outside of 10 % threshold that is generally deemed to be reliable. It was discussed that the successful adherence to the framework of considerations outlined in chapter 3 contributed towards the success of the test-retest reliability analysis. However, the difficulties of collecting true maximal voluntary contractions in the applied field was also discussed as a limitation of the study, which may have perhaps contributed to the small emergence of measurement error that some of the measures held (systematic bias). It was concluded that every effort should be made to standardise strict conditions upon collecting data, especially when decisions are to be made on results that assessment tools provide. Such conditions would be inclusive of eliminating interaction from non-participating athletes and maintaining consistent motivational environments for each athlete.

7.1.5. **Objective 5.** To investigate the association between isometric hip extension strength measured with the HEB assessment tool and sprint-acceleration and jump performance.

The final objective of the project was addressed in chapter 6. Upon the successful investigations surrounding the sensitivity and reliability of the HEB assessment tool, the first implementation of the tool was made within an exploration of the relationship between isometric hip extension strength and sprint-acceleration and jump performance. For this investigation, 10 competitive sprinters completed 40 m sprint-acceleration trials and various assessments of jump ability to determine their athletic ability of HIE performance. In order to understand the association between isometric hip extension strength and HIE performance, the sprinters also completed bilateral and unilateral maximal contractions on the HEB assessment tool.

The main findings from chapter 6 indicated that isometric hip extension strength is significantly associated with sprint-acceleration and jump performance in the forwards direction. These associations were significant in force-based indicators of sprint-acceleration (F_0, $F_{\text{H Mean}}$, $F_{\text{T Peak}}$, $P_{\max}$ etc) but not for velocity-based indicators (V_{Max}, V_0, 2, 20 & 40 m, etc). Regarding jump performance, isometric hip extension strength was significantly associated with horizontal jumping but not with vertical jumping. The findings from this study indicate that isometric hip extension strength is important for sprint-acceleration and jump performance, especially for the development of specific facets of performance such as maximal force production and force in the forwards direction. As such, it was hypothesised that increasing the force generating capacity of the hip extensor muscles through training interventions may have positive transfer over to athletic performance and HIE capacity.

7.2. General discussion

7.2.1. Additions to current scientific knowledge

Investigations from this thesis add to the wealth of literature surrounding the assessment of muscle strength in sports science. The unique avenue that has been explored provides the world of sports science research and applied sport with a novel assessment tool to assess isometric hip extension strength. The numerous distinctive aspects of the HEB assessment tool place it as a suitable and robust device for application in future research or applied world settings to aid practitioners further understanding of the physical profile of their athletes. Such findings may subsequently be used for measuring the physical development of athletes and efficacy of training interventions on a longitudinal basis, or perhaps in an acute setting to assess athlete fatigue status in response to competitive demands.

The applied nature of the project also provides an uncommon addition to the literature of real-world expectations, constraints and limitations when performing research with competitive athletes in time-constrained environments. Many of these factors are not often discussed in traditional research yet can provide increased complications at ground level. Therefore, such complications may lead to an inability to implement many of the recommendations and findings that are presented in traditional research investigations. As such, the findings of the present study may have increased relevance and applicability to practitioners within similar fields whom may encounter similar environments and therefore may be of greater use than research within more clinical environments.

Aside the environmental considerations, findings presented in this thesis add to the growing evidence at present that propose hip extension movement as an important factor for HSI mitigation. The limited available research surrounding the general selectivity of G_{max} and hamstring muscles during isolated hip extension contractions has been added to with the use of a novel and comprehensively developed assessment tool. The general beliefs of delayed G_{max} muscle activation patterns during hip extension was also confirmed within the present research, with further suggestions surrounding the homogeneity of this factor across a range of hip flexion angles

As well as considerations surrounding the activity of the hip extensors during isometric contractions, the findings in chapter 6 ensure that practitioners can view isometric hip extension strength as a relevant measure and action for sprint-acceleration and jump performance. The dynamic performance of hip extension exercise and measurement variations have already been shown to be important factors of physical performance, yet their application in real world environments isn't always feasible. Therefore, the present findings can fill the gap in research for a measure of isometric hip extension strength to provide similar relatedness to these actions.

Finally, throughout the data collection period a substantial amount of information was retrieved across all age groups of elite soccer players. As such, the data presented below (table 7.1) provides a robust set of normative values for practitioners on the maximum force generating potential of soccer players' hip extensors under isometric conditions that previously has not been available. Where blanks are present, no data has been collected for that respective age group or assessment position at present.

Table 7.1. Normative values for isometric hip extension maximum force measured with the HEB (values presented are average ± SD, N/kg$^{0.67}$).

Age Group	No. athletes (n)	HEB$_{70}$	HEB$_{60}$	HEB$_{45}$	HEB$_{30}$	HEB$_{15}$	HEB$_{0}$
1st Team	33		97 ± 20			73 ± 22	
U23’s	23	100 ± 20	96 ± 12	93 ± 15	86 ± 16	77 ± 12	67 ± 18
U18’s	23	99 ± 16				69 ± 13	72 ± 20
U16’s	21	95 ± 14					89 ± 35

When addressing values attained from assessing an athlete’s maximal hip extension strength, it is possible for practitioners to base the necessity of subsequent interventions on comparisons to squad or positional averages. For instance, a simple method of categorising athletes in groups, determined by an arbitrary level of standard deviations above or below a squad average (good = average + SD, poor = average – SD), can provide useful information (Buchheit, 2016) on those who may need specific programming to target the maximum force capacity of the hip extensor muscles. In addition, practitioners may wish to utilise the normative values presented in table 7.1 to make comparisons. However, it is important to consider that these values are from an elite soccer cohort so comparisons to other sports or levels of play may not always be suitable. After determining those that are deemed weaker according to the assessment, it may then be suitable to begin a period of intervention targeting the specific capacity that is deficient, i.e. maximal hip extension strength.

7.2.2. Practical application and implications

It is anticipated that the information presented within section 3.1 of chapter 3 will encourage practitioners and researchers to follow the same rigorous approach when developing and utilising assessment tools within research and the applied field. Within professional sport, there is a countless availability of data through an abundance of collection modalities and it can be easy to get caught in the athlete monitoring minefield of data. Therefore, the researchers recommend that prior to selecting and applying assessment tools within one’s field, a thorough needs analysis is developed and a critical evaluation of the tools available is made. In addition, within professional sport the possibility of informing crucial decision-making situations confirms the level of rigour that must be held surrounding assessment tool validity and reliability. For example, inaccurate representations of an athlete's hip extension strength capacity during baseline testing may result in ineffective programming of future training blocks. Alternatively, coaches may be ill-advised when making decisions on an athlete's ability to train and compete if used as a fatigue monitoring tool.

When addressing values attained from assessing an athlete's maximal hip extension strength, it is possible for practitioners to base the necessity of subsequent interventions on comparisons to squad or match positional averages. For instance, a simple method of categorising athletes in groups, determined by an arbitrary level of standard deviations above or below a squad average (good = average + SD, poor = average – SD), a z-score, can provide useful information on those who may need specific programming to target the maximum force capacity of the hip extensor muscles. In addition, practitioners may wish to utilise the normative values presented in table 7.1 to make comparisons. However, it is important to consider that these values are from an elite soccer cohort so comparisons to other sports or levels of play may not always be suitable. After determining those that are deemed weaker according to the assessment, it may then be suitable to begin a period of intervention targeting the specific capacity that is deficient, i.e. maximal hip extension strength.

It has been confirmed that inefficient and suboptimal coordination of hip extensor activation patterns may cause undesirable hip joint motion and unfavourable torque distribution across the muscles during running (Tateuchi *et al.*, 2012; Schuermans *et al.*, 2017b; Chumanov *et al.*, 2007). Therefore, improving the synergistic role of the G_{max} to stabilise the hip and possibly offload the hamstrings may prove an advantageous adaptation to achieve. Possible methods of doing so may include the recommendations from previous authors to alter body positioning during hip extension tasks to enhance G_{max} muscle activation (Kang *et al.*, 2013; Lehecka *et al.*, 2017; Macadam & Feser, 2019; Choi *et al.*, 2015; Collazo-Garcia *et al.*, 2018). Future research may wish to investigate specific interventions to improve these factors.

Regarding implementation of the HEB assessment tool, results from this thesis should provide practitioners with confidence surrounding its validity and reliability. Direct comparisons to previous measures of hip extension strength were not made within this research due to the belief that a gold-standard did not exist. Because of this, simply comparing an insufficient tool to the HEB seems impractical and not particularly useful. For this reason, it cannot be said whether the HEB is more of less reliable and accurate in the specific cohorts that were tested in this population. It is also the research groups belief that a comprehensive analysis of any assessment or training tool should be completed prior to implementation within any environment, yet such actions are not always taken. In the present data set, a comprehensive analysis of muscle activity and force production during isometric hip extension was undertaken in chapter 4. These findings provide a set of standards and recommendations for the implementation of hip extension assessment tools in practice, to ensure that threats to increasing measurement error are minimised. In addition, the transparent conclusions surrounding test-retest data collection in the applied field of elite soccer and can be used to apply similar methodologies in other environments. The minimal difference is described to be specific to the cohort of which it is obtained, so practitioners are urged to complete such checks with their own cohort of athletes. With that being said, those working in similar environments may wish to use this data to apply to their own populations when provision to do so is not possible.

With respect to improving physical performance, the findings from chapter 6 can be replicated and utilised in practice in order to assess athletes in different environments. Implementing the HEB assessment tool in practice can provide practitioners with useful information on the force generating capacity of a crucial joint action for HIE performance. As such, individualised training interventions may be programmed tailored towards the specific needs of the athlete. For instance, if an athlete deemed “slow” performs poorly during HEB strength assessments, it may be feasible to suggest that a training intervention targeting the strengthening of the hip extensors will provide desirable adaptations and improvements.

7.2.3. Making decisions in applied practice

Aside the specific findings of the present studies, the research team seeks to remind the reader of the significantly precise avenue of the present research. Hip extension is one of many joint actions that contribute towards athletic movement, which is one of many important aspects of sports performance. Having the ability to understand the wider picture when working within a multidisciplinary environment and understanding the importance of the various other disciplines that contribute towards the same goal is crucial. One must be aware of the constraints of the working environment and respect the various other elements to successful sports performance in order to work in accordance and not discordance.

Before employing new methods to assess athlete performance, consideration for the environment for which it is to be used is also required. At ground level, the time constraints of professional sport may raise questions surrounding how often assessments can and should be taken. Regarding training, a question must also be asked of what the smallest dose of training is that one can expect to see adaptations from, and which training methods should be prioritised when there is time available to train. It is also important to consider whether the limited time available and level of buy-in from athletes is sufficient in order to actually collect useful data or expect positive adaptations.

Some of these applied and real-world reasons are why rigorous and robust methods such as the ones found in the present research have been and should be undertaken. For example, several aspects of the HEB assessment tool can now indorse the use of the device within the applied setting. For example, the isometric nature of muscle contraction minimises muscle damage and fatigue susceptibility to allow it to be implemented in congested and demanding schedules. In addition, the valid and reliable setup reassures practitioners when using data to inform important decisions on a daily basis. The sensitivity of the tool allows practitioners to detect precise differences in muscle behaviour which may contribute to an increased understanding of injury susceptibility. Finally, the close association that the HEB strength assessment tool has with force-based indicators of sprint-acceleration performance and horizontal jumping, can provide practitioners with a strong rationale for the addition of such devices in their strength and conditioning battery of diagnostics.

7.3. Recommendations for future research

With the above in mind, the following recommendations have been developed for future application and research within hip extension strength assessment and training.

7.3.1. Further investigation of reliability and validity of the HEB in a variety of populations.

Considering the relatively specific and sometimes small (in chapter 4) population samples investigated in the present research, further investigations of the HEB's reliability and validity in a variety of populations is warranted to determine its suitability across different sports, playing levels and age groups. For instance, within different sports and competition levels, athletes may be exposed to resistance training and testing at different magnitudes. In addition, the requirement of the hip extensors for successful performance is largely dependent on the actions required within the sport. Therefore, the position of a maximal assessment of strength for the hip extensors may differ considerably and athletes' physical attributes may somewhat influence the suitability of the assessment itself (Buckner *et al.*, 2017). After the collection and interpretation of data across the different populations, the certification of the HEB as a suitable assessment tool for providing information on maximal isometric hip extension strength will be granted.

7.3.2. Prospective and longitudinal investigations into the relationship between hip extension strength assessed with the HEB and HSI susceptibility

It has been hypothesised that increasing the G_{max} and Add_{mag} as synergists to the hamstrings may act to offload the muscle during times of increased loading (i.e. sprint-acceleration). As such, an interesting avenue to explore may be whether a baseline level of hip extension strength or muscle excitation assessed with the HEB is able to determine, predict or explain subsequent HSI susceptibility and occurrence in various sporting populations. In this case, findings from the present study may be utilised primarily as baseline/normative data in order to build from. The collection of neuromuscular behaviour during isolated hip extension contractions may be used to represent "normal" and "healthy" function and identify those who may present patterns of activation that place them at risk of sustaining injury in the future.

7.3.3. Further investigations surrounding hip extension directed training and HSI management

Emerging evidence is pointing towards the direct and indirect influence of the hip extensors for the positive management of HSI. However, it is yet to be seen whether factors relating to increasing G_{max} or Add_{mag} muscle strength and activation patterns leads to a reduction in HSI prevalence. Further studies understanding the selective activation of the BF_{lh} in response to hip extension directed training are also warranted.

7.3.4. Isometric training interventions to improve physical performance

Substantial evidence exists to explain the effectiveness of isolated hip extension training for improvements in HIE performance. However, replication of these interventions is not always feasible in the applied field. As such, it may be of interest to determine whether a period of isometric training of the hip extensors as a less physiologically taxing method of training can improve levels of physical performance. The relationship between isometric and dynamic force-time characteristics is generally considered to be strong (Lum *et al.,* 2020) and periods isometric strength training can generally carry over to dynamic performance (Lum & Barbosa, 2019). The adaptations to isometric training methods are also well presented and generally promote its usage for improvements in muscle hypertrophy, maximum force production, rapid force production and tendon structure (Oranchuk *et al.,* 2018). With this in mind, the following text outlines the research team’s recommendations for when attempting to utilise the HEB assessment tool as a training device. It is important to also clarify that the proposed recommendations for magnitude, duration and type of isometric contraction are not based on objective findings from this thesis but from a combination of available literature and applied experience from practitioners in the field. The specific joint angle proposed for development of specific muscles is however guided by findings from the present thesis, within chapter 4.

As maximum strength development is the aim for each of the following recommendations, according to Lum and Barbosa (2019) isometric training should be performed at 80-100% maximal voluntary contraction. In addition, considering the large importance of RFD in sports performance, it is also advised that ballistic contractions are to be prescribed by practitioners in order to improve rapid force development (Lum & Barbosa, 2019; Oranchuk *et al.*, 2018).

In order to selectively target and improve G_{max} maximum strength development during isometric training, the research team propose an contractions at angles of 0-15° ($HEB_{0/15}$). In order to target the hamstrings, angles of greater hip flexion are recommended ($HEB_{60/70}$). Training at greater hip flexion may be especially useful for transfer to dynamic performance due to the superiority of long muscle length isometric training when compared to short (Oranchuk *et al.*, 2018).

Regarding the type of contraction, an isometric "push" has been suggested to mimic overcoming an isometric i.e. concentric contractions that are important during ground contact during sprint running to propel the COM forwards. As such it may be recommended that this form is greatest for the G_{max} targeting position. An isometric "hold" or "catch" has been suggested to better mimic successful braking by resisting the eccentric or quasi-isometric actions that the hamstrings undergo during swing, so may be better suited for the hamstring targeting position. However, to the research team's knowledge literature to support such theories is absent.

Specifics of basic volume and intensity recommendations can be found in table 7.2. below and are based upon available literature and practitioner anecdotes, yet it is suggested that practitioners' experiment within their own cohort to develop a suitable and bespoke programme for their athletes.

Table 7.2. Recommendations for isometric training on the HEB

Goal	**Exercise Type**	**Cues**	**Volume**
G_{max} maximal and rapid force development	ISO_{push} – $HEB_{0/15}$	3 – 5 s, 80-100% MVC with rapid intent	80-150 s total
Hamstring maximal and rapid force development	$ISO_{hold/catch}$ – $HEB_{60/70}$	3 – 5 s, 80-100% MVC with rapid intent	80-150 s total

(ISO_{push} = isometric push, $ISO_{hold/catch}$ = isometric hold/catch, s = seconds, MVC = maximum voluntary contraction)

**recommendations are based on empirical evidence and previous literature, not findings from the present thesis.*

7.3.5. Neuromuscular fatigue monitoring

Considering the prevalence of HIE’s in professional soccer, it is assumed that athletes may endure increased neuromuscular fatigue to specific regions of the body. As such, traditional methods of interpreting neuromuscular fatigue in response to competition may not be sensitive enough. As such, implementing a measure such as the HEB assessment tool may provide practitioners with a more sensitive description of their athletes’ ability to cope and recover with the competitive demands of soccer. Such information may be useful when determining recovery strategies between competition or understanding which players may be having difficulty when coping with the demands of soccer match play.

7.3.6. Evolution of the Hip Extension Bench

The current HEB assessment tool may have potential to be improved in future research and development. The improvements may surround load cell selection for data collection, as it may be of interest to collect measures with a greater sampling frequency (500 Hz +) in order to represent a measure of rate of force development. Alternatively, although the HEB is a portable assessment tool, choosing materials that are lighter in mass or that have the capacity to fold to a smaller size may improve the transportability of the tool during travel to and from competitive fixtures or during pre-season tours, for example. This way, it will be possible to assess and train no matter what location the athletes are in. Finally, further reliability and validity investigations with larger cohorts of various sports may be interesting. That way, greater confidence can be had when determining the global reliability and validity of the HEB strength assessment tool.

7.4. Conclusion

The aim of the thesis was to investigate maximal hip extension strength in professional soccer with respect to assessment and physical performance. The primary outcome of the project was the successful development of a novel assessment tool for measuring isometric hip extension strength. The assessment tool was then applied to several rigorous checks in order to understand its suitability for use within an applied sports science setting. During these investigations, the sensitivity of the tool was confirmed where detection of changes in force and muscle activity are distinguishable (HEB_{0-15} vs. HEB_{60-70}) and the reliability of the tool was confirmed through a thorough test-retest analysis. It was suggested that the HEB assessment tool may also provide a means of understanding various prospective HSI related factors during isometric hip extension contractions. In addition to this, the association of isometric hip extension strength to sprint-acceleration and jump performance was confirmed in a population of competitive sprinters.

In summary, findings from the present research endorse the HEB strength assessment tool as a useful tool for practitioners to utilise and implement in their respective environments. Importantly, it is recommended that the HEB strength assessment tool is implemented alongside various other assessment types in a holistic battery of diagnostics. Then, data that is collected with the HEB assessment tool may be utilised in combination with other variables to inform subsequent training interventions with a goal of improving physical performance, reducing injury risk and consequently enhancing the opportunity for achieving success in the athletes' given sport.

Chapter 8

Reference List

Reference List

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