Hamstring Muscle Strength Assessment and the Association with Injury Risk in Gaelic Football.

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Volume 1 of 1

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any university or other institute of learning.

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The work, to date, has been extremely enjoyable both from an academic and clinical/commercial aspect. My academic journey began at LJMU completing a BSc in Sports Science in 1996, MSc in the Physiological profiling elite Gaelic footballers at the Institute of Technology Tralee in 2003 and also a M.Med.Sci in Sports Medicine at the University of Sheffield, in 2006. During this time I have worked as a sports scientist, exercise physiologist and now work primarily in the sports medicine field, in which I have worked since 2007 and run my own clinic the Sports Injuries and Sports Medicine Clinic. Balancing both my academic and professional work was challenging. Currently I have a patent application filed with a view to launching the H Rig commercially into the Irish market Q3, 2022. This concept, evolved through some of the research detailed in this thesis and also additional work, testing and prototyping carried out on over 500 athletes. Publications for Study 1, Eccentric Hamstring Strength in Club Gaelic Footballers. ISBS 2021 Proceedings Archive: Vol. 37 : Iss. 2, Article 1. https://commons.nmu.edu/isbs/vol37/iss2/1; Study 2 Reliability and bilateral strength imbalances of a new isometric test to identify previous hamstring strain compared to eccentric strength. ISBS 2022 proceedings archive https://commons.nmu.edu/cgi/viewcontent.cgi?article=2342&context=isbs&z=1647861781&preview_mode=1&login=3261795. An abstract entitled “Pre-season and late In-season eccentric strength and its relationship to hamstring injury in Gaelic footballers was also accepted to SportKongress 2022.

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Abbreviations

AKE	Active knee extension
AM	Adductor magnus
ACSA	Anatomical cross-sectional area
BF	Biceps femoris belly
BFlh	Biceps femoris long head
BFsh	Biceps femoris short head
EFOV	Extended field of view
fH:Q	Functional Hamstring to Quadriceps Strength/peak torque ratio
GF	Gaelic football
H_{opp}:H_{opp}	Hamstring-to-opposite hamstring
H_{con}/Q_{con}	Conventional hamstring to quadriceps strength/peak torque ratio
HSI	Hamstring strain injury
IKD	Isokinetic Dynamometer
Iso_{BI}	Isometric bilateral hamstring strength
Iso_{UNI}	Isometric unilateral hamstring strength
L_f	Fascicle length
ms	Milliseconds
MRI	Magnetic resonance imaging
MVIC	Maximum voluntary isometric contraction
NB_{Ecc}	Nordic maximal eccentric torque

NHE	Nordic Hamstring exercise
PSCA	Physiological cross-sectional area
PSLR	Passive straight leg-raise
PT	Peak Torque
RR	Univariate relative risk
RTD H/Q	Rate of torque development of the hamstrings and quadriceps
SM	Semimembranosus
ST	Semitendinosis
VAS	Subjective visual analogue scale
θ_p	Pennation angle

Abstract

McIntyre, M. Hamstring Muscle Strength Assessment and the association with Injury Risk in Gaelic football.

It is important to identify strategies to help minimise and reduce the risk of hamstring injury and subsequent re-injury in Gaelic football, particularly given the high incidence of hamstring injuries and the level of recurrent injuries within the sport. There are a number of predisposing risk factors of which hamstring strength, has been proposed as a modifiable risk factor, in which interventions are reported to reduce the incidence of injury and risk of re-injury. Therefore, this research investigated various modes of hamstring strength assessment and its association with hamstring strain injury.

Study 1 : Nordic maximal eccentric torque (NB_{Ecc}) of the hamstrings was tested for 67 players during pre-season and late in-season using the Nordic hamstring exercise (Nordbord system™). Maximal force, maximal torque in both the pre and in-season were analysed and univariate relative risk (RR) were used to determine future HSI. Eccentric hamstring strength levels over the season were not predictive of hamstring injury occurrence in Gaelic football players, although a minimum level of strength (120 Nm) is required.

Study 2 : A novel device, specific to the mechanism of injury in late swing/early stance was developed to evaluate isometric bilateral hamstring strength (Iso_{BI}). 70 amateur Gaelic Footballers were assessed where a moderate to high reliability was reported. Isometric strength testing better identifies those with residual strength deficits following HSI in the previous season, with strength levels below 150Nm suggestive of previous HSI.

Study 3 : Subsequently a unilateral hamstring strength (Iso_{UNI}) test was developed. A total of 35 non-elite (club) GF players were tested on two separate occasions to determine the test-retest reliability of the new Iso_{UNI} assessment where a moderate to high reliability was reported.

Study 4 : A novel hamstring strength battery was undertaken to determine the relationship of NB_{ECC}, ISO_{BI}, Iso_{UNI} and also isokinetic (IKD) metrics in HSI. A total of 49 amateur Gaelic club Football players underwent NB_{ECC}, ISO_{BI}, Iso_{UNI} and IKD assessment at 60^0/s and 180^0/s. Residual isometric and eccentric IKD torque weaknesses exist in previously injured players, with IKD ratios for opposite hamstring to hamstring, conventional and functional ratios all lower in players with previous HSI.

Study 5 : Fascicle length (L_f) and pennation angle (θ_p) were determined and their relationship to HSI assessed. In total, L_f and θ_p was determined in 49 amateur Gaelic club Football players and compared to the battery of strength testing from Study 3 where players were tested in pre-season. There was a trend towards lower but non-significant Biceps Femoris long head (BFlh) L_f in those with previous HSI. L_f was related to isometric strength and not NB_{ECC}. There were only 4 prospective HSI injuries identified during the shorter playing season (due to Covid).

Study 6 : 30 players with HSI were clinically assessed (0-7 days post injury) by an experienced clinician and underwent Iso_{UNI}, Iso_{BI}, and NB_{Ecc} tests to examine the diagnostic accuracy of these isometric tests for HSI classification. A high level of agreement and correlation between Iso_{UNI} and clinical assessment was reported in the classification of HSI which can aid the diagnosis and classification of HSI.

Summary : NB_{ECC} strength is not predictive of previous HSI. ISO_{BI} and ISO_{UNI} tests, both with moderate to high reliability better identifies those with residual strength deficits following HSI. Lower hamstring isometric strength and IKD eccentric torque, bilateral hamstring deficits in peak torque, conventional and functional ratios exist in previously injured players. Isometric strength deficits which identify residual deficits had a strong relationship to L_f and have a tendency to be shorter in players with previous HSI. It is recommended that the ISO_{BI}, ISO_{UNI} and IKD ratios at 60^0/s be used to screen for previous hamstring injury, while the ISO_{BI}, ISO_{UNI} be utilised to aid in the diagnosis and classification of HSI following acute injury.

Chapter 1

Introduction

Gaelic football (GF) is Ireland's national sport, multidirectional in nature with bouts of high intensity and combines various facets of Soccer, Australian Rules Football and Rugby (Cullen et al., 2013). Gaelic football is played with 15 players, using a round ball on a rectangular pitch measuring 90 m x 140 m and games are divided into two 35-minute halves at elite level, while sub-elite games are less (30mins). At sub-elite (club) level a county-based competition is run with each local club in each county divided according to locality, in which, the season can run from February to November.

The game is physical (Reilly and Doran, 2001) with players covering on average 132 $m.min^{-1}$ and this can increase to 230 $m.min^{-1}$ (Malone et al., 2017). The game exposes players to high levels of physiological strain with peak heart rates of 195 ± 9 $b.min^{-1}$ where average heart rates can vary according to playing quarter (1st Quarter 160 ± 9; 4th Quarter 165 ± 12 $b.min^{-1}$) (Reilly and Doran, 2001, Gamble et al., 2019). Fatigue is a factor towards the end of games with a decremental reduction from quarter to quarter, evident in sprinting speeds ($\geq$6.1 $m.s^{-1}$) (Malone et al., 2017, Gamble et al., 2019, Waldron and Highton, 2014, Mooney et al., 2013). Running speeds are on the increase (Table 1.1) in which HSI becomes particularly prevalent with increases in high-speed running distances (Brooks et al., 2006, Duhig et al., 2016, Colby et al., 2014), (discussed in more detail later in Chapter 2). These facets of the game predispose players to injury, in particular to hamstring strain injury (HSI), the most common injury within the game (23.9% of all injuries) (Roe et al., 2016).

Table 1. 1: *Top speeds of Mayo Senior football team in All-Ireland finals. (unpublished data).*

	2017	**2019**	**2021**
$km.h^{-1}$	34.2	35.0	35.8
$m.s^{-1}$	9.5	9.7	9.9

It is estimated the injury burden of HSI is €1.6-€2.4 million (Murphy et al., 2012), a twofold increase in HSI has been reported from 2008/2011 to 2012/2015 (Roe et al., 2016), an average of 26 days lost from play (Roe et al., 2018b), there is a high recurrence rate 36% (Roe et al., 2016) and the issue in GF is higher than other field sports (Roe et al., 2016, Ekstrand et al., 2016, Orchard et al., 2013). The aetiology of injury is multifactorial. There are a number of non-modifiable and modifiable risk factors associated with HSI and these are outlined in more detail in Chapter 2. Non modifiable risk factors such as age (OR = 2.9, $p < 0.05$) and previous hamstring injury (OR = 3.7, $p < 0.01$) are strong risk factors for future hamstring injury. Modifiable risk factors are not as strong statistically, but nevertheless strength is seen as an important risk factor, eccentric torque (OR = 2.1, $p = 0.35$) and isometric strength deficits exist in players with previous HSI (Smith et al., 2021, Maniar et al., 2016). Strength interventions are common as it is a modifiable risk factor and widely regarded as a preventative measure (Opar et al., 2014). Implementing the Nordic hamstring exercise has been reported to reduce HSI in sub elite soccer players by 50-70% (Peterson and Gordon, 2011, van der Horst et al., 2015). An emphasis and focus on strengthening the hamstrings in long lever positions is also seen to be effective in reducing time to play following injury (Askling et al., 2014). Some multifactorial screening programs have also been devised in order to prescribe intervention programs for HSI prevention. These have included intrinsic and modifiable risk factors in which hamstring strength is an important component of the screening process (Lahti et al., 2020).

Hamstring strength and its ability to withstand running loads is important as running is the main mechanism (73%) of injury in GF, where injury occurs at high speed (Roe et al., 2018b, Wilson et al., 2007). The hamstring has potential for injury either in late swing or early stance, however direct evidence is lacking as it is difficult to study the kinematics of HSI (see Chapter 2). Strength is a pre-requisite for running performance as peak hamstring forces are reported to occur in late swing and early stance where the hamstrings are vulnerable and predisposed to injury (Figure 1.1) (Higashihara et al., 2018). Eccentric, isometric and also to a lesser extent concentric strength have various applications to the tolerance of running load, however most focus to date has concentrated on eccentric strength as the literature has suggested that during late swing phase the high forces cause fascicles to act eccentrically and there therefore exists a vulnerability for structural damage (Van Hooren and Bosch, 2017).

Figure 1. 1: *The late swing phase in gaelic football – the vulnerable phase to HSI, Where the hamstrings act eccentrically and you will notice the hamstrings in a lengthened position (long lever position).*

The Nordbord testing system™ is one system which assesses the eccentric strength of the hamstrings (Described in Chapter 2). It has been suggested that elite Australian rules footballers with hamstring strength levels below 256N at the start of the season are 2.7 times more likely to sustain a hamstring injury (Opar et al., 2015). More recently this test has caused debate, as it does not control the speed of movement while it may also only assess strength in inner range, where the hamstrings are in a shortened position with a break point angle of 40^0 (Roe et al., 2020, Opar et al., 2015, van Dyk et al., 2017). Data during this test is widely reported in force (N) rather than a torque moment (Nm) and there is very little consensus on its value for retrospective and prospective HSI risk (van Dyk et al., 2017). Investigating this data in relation to Gaelic footballers and specifically looking at joint moments rather than force may help clarify some this debate.

Isokinetic dynamometry (IKD) is another method of assessing eccentric hamstring strength. It has been suggested weak eccentric hamstring strength via IKD measurements is associated with the risk of hamstring muscle strain in soccer players (Fousekis et al., 2011). However, there are mixed findings within the literature for IKD with respect to HSI risk and the main concerns pertaining to this are 1) alignment of the central axis around the head of the dynamometer 2) mode of testing 3) angular velocity 4) contraction type (all discussed in more detail in Chapter 2). Investigating IKD with a novel protocol and setup to minimise errors in measurement will provide a useful insight into HSI risk in GF, as it has not been previously studied.

One area that also requires further investigation is isometric strength, which is not well researched, relatively inexpensive, safe and quick to utilise. Maximal isometric knee flexion peak force, torque and normalised torque measures are reduced following injury (Charlton et al., 2018b). An alternate hypothesis is one where a quasi-isometric contraction exists in the swing phase prior to HSI (Figure 1.2). This is not widely accepted nor widely researched, nevertheless given the lack of consensus on the relationship of eccentric strength to HSI and with HSI injuries on the rise it is worth considering an alternative approach investigating isometric strength and its relationship to HSI in which the posture of the athlete better reflects the mechanism of injury in late swing/early stance and may provide more sensitivity in detecting residual deficits. It is worth considering these alternative or novel approaches which replicate the mechanism of injury in late stance given the lack of sensitivity and consensus on current methods. Particularly as residual weaknesses may still exist following injury given the high recurrence rate (44%) (Roe et al., 2016).

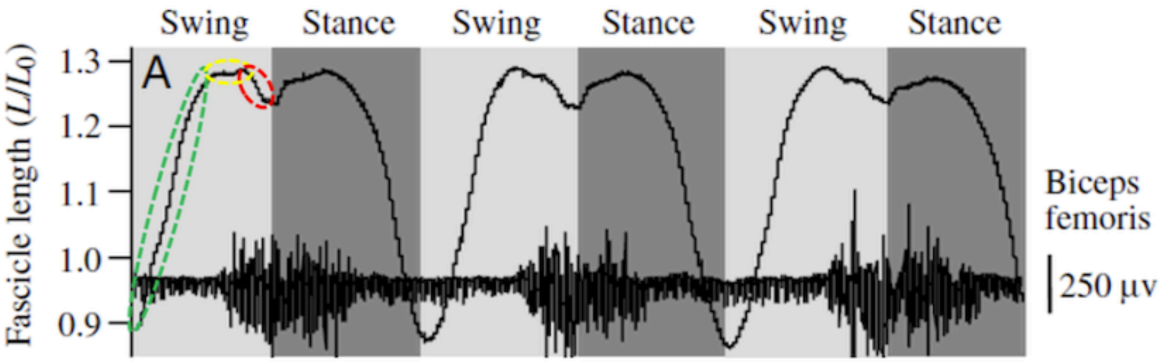


Figure 1. 2: *BFlh Fascicle length and muscle activity during three strides of trotting at 2.0 m.s^{-1} (Gillis et al., 2005).*

Even though this is in a goat trotting this has been widely debated and postulated where it is possible for it to occur during human locomotion. During early swing phase in green you will see fascicle lengthening, then isometric contraction in yellow, finally fascicle shortening in red in preparation for the stance phase.

In terms of strength, underlying hamstring morphology and architecture play an important role in HSI risk as it determines the mechanical output of the muscle (Fiorentino et al., 2012). In particular, Fascicle length (*L*f), refers to the length of the muscle fascicle which is measured from the deep intra muscular tendon (aponeuroses) to the superficial tendon.

Secondly pennation angle (θ_p), the angle at which these muscle fascicles attach to the aponeuroses (Timmins et al., 2016a) are important factors to consider when investigating the effect of a mechanical stimulus on muscle and its ability to withstand external forces (Potier et al., 2009). This can be key in determining internal muscle strain magnitude (Fiorentino et al., 2012) and important when evaluating the factors predisposing to injury (Mendiguchia and Brughelli, 2011). Shorter BFlh L_f increase the risk of future HSI (Timmins et al., 2016b). L_f in the BFlh of the injured limb is significantly shorter than in the un-injured limb in male athletes (Timmins et al., 2014) and also in previously injured soccer players (de Lima-E-Silva et al., 2020). This is an important consideration when muscle lengths approach and exceed 100% of resting length with increases of 40mm (from resting values) required in late swing/early stance (Figure 1.3) (Thelen et al., 2005b).

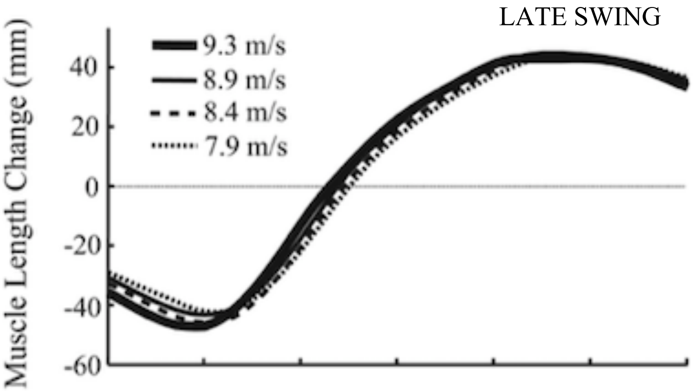


Figure 1. 3: *Muscle length changes during the gait cycle (Thelen et al., 2005).*

You will see that the hamstrings are required to stretch to over 40mm of resting muscle length in late swing/early stance. This requires muscle fascicles to be longer and more pennate as there is a requirement on the proximal portion of the hamstrings to tolerate this lengthening during late swing/early stance..

In assessing both L_f and θ_p to date the majority of studies have used a method where the whole muscle fascicle is not evident and as a result L_f has to be estimated using trigonometric equations. Another method know as extended field of view (EFOV) in which the whole muscle fascicle is evident and can be measured directly has also be used but is not as common due to the technology required and as a result the majority of architectural studies to date have used estimated methods (Potier et al., 2009, Blazevich et al., 2006, Finni et al., 2001). However estimation and extension of this data by up to 50% is required (Franchi et al., 2018) and not as accurate as EFOV (Pimenta et al., 2018). Therefore, data in the literature is overestimated as trigonometric equations tend to overestimate but also on occasions underestimate Lf (Franchi et al., 2019, Noorkoiv et al., 2010). Utilising EFOV to measure BFlh Lf would help address this debate within the literature and provide useful and novel information as to whether BFlh architecture can be considered a risk factor for HSI in GF.

Following acute HSI muscle injury classification systems provide diagnosis, prognosis and aid in the rehabilitation and return to sport following injury. There are a number of systems which have evolved from the first system (O'Donoghue, 1958) to more recent systems from British athletics', Munich and Barcelona (Mueller-Wohlfahrt et al., 2013, Valle et al., 2017, Pollock et al., 2014). There is limited evidence within these new classifications systems for predicting return to play following HSI and the high costs and availability of magnetic resonance imaging (MRI) may exclude the use of this modality in general day to day clinical use. It is also not required for diagnosis of minor or moderate HSI in professional footballers (Schneider-Kolsky et al., 2006). These classification systems although biased towards MRI, also require corroboration in the form of clinical assessment with palpation, subjective visual analogue scale (VAS), active knee extension (AKE) and passive straight leg raise (PSLR) (Boonstra et al., 2008, Schneider-Kolsky et al., 2006, Maniar et al., 2016, Reurink et al., 2013, Askling et al., 2007). Strength testing to date has been used widely to investigate underlying pathologies and risk of HSI but no agreement has been reached with muscle injury classification for diagnostic purposes. Generally clinicals have used VAS scale when strength testing injured athletes and there is no objective data available to support clinical examination and diagnosis of HSI in which there is a need for relevant tests with discriminative and predictive ability (Heiderscheit et al., 2010).

Losing players to initial and recurrent hamstring injuries over the last 16 years whilst working in elite sport, has been particularly frustrating and extremely stressful. Over this time I have employed some novel strategies (designing isometric and eccentric accelerated recovery programs and normative data for return to play profiling) and used these devices to provide objective information in supporting the decision making process on the risk of HSI in the sport and in an attempt to minimise recurrent injuries. Given the trends within the research in which hamstring incidence is rising and the debate surrounding the most prominent risk factors or even the lack of consensus within hamstring risk modelling, has promoted me, over the last 7-8 years to reflect on specific clinician solutions and trends in a more detailed manner to troubleshoot in this particularly troublesome area of HSI. Therefore, the overall aims and hypotheses contained hereafter is driven by a combination of over 15+ years of clinician experience with careful consideration given to the scientific research currently existing within the literature. The following series of studies will investigate strength testing, including a novel method and its relationship to HSI and will also attempt to provide clinicals with objective strength data to classify HSI following acute injury.

Study Aims

The research began with NB_{ECC} assessment to determine its relationship to HSI, following this studies progressed, in a logical order to investigate more novel modes of hamstring testing.

1. Study 1 - Compare pre-season and late in-season NB_{Ecc} torque between injured and un-injured Gaelic football club players.
2. Study 2 - Determine the reliability of a novel Iso_{BI} test in measuring isometric hamstring strength in Gaelic football club players and compare eccentric and isometric strength in respect of previous HSI.
3. Study 3 - Determine the reliability of a novel Iso_{UNI} test in measuring isometric hamstring strength.
4. Study 4 - Compare IKD, Iso_{BI}, Iso_{UNI} and NB_{Ecc} strength in Gaelic football club players with previous HSI.
5. Study 5 - Compare the architecture of the BFlh in injured and un-injured Gaelic footballers club players and assess the relationship between L_f, θ_p and NB_{Ecc}, Iso_{BI}, Iso_{UNI} strength.
6. Study 6 - Compare Iso_{BI} and Iso_{UNI} strength in the clinical diagnosis of HSI in Gaelic football club players with HSI.

Study Hypotheses

1. Study 1 - NB_{Ecc} torque is lower in preseason in those players experiencing HSI during the playing season.

2. Study 2 - A novel Iso_{BI} test is reliable in measuring isometric hamstring strength in Gaelic football club players and is lower in players with previous HSI injury.
3. Study 3 - A novel Iso_{UNI} test is reliable in measuring isometric hamstring strength
4. Study 4 - IKD, Iso_{BI}, Iso_{UNI} and NB_{Ecc} strength is lower in Gaelic football club players with previous HSI.
5. Study 5 - L_f, θ_p are both lower in players with previous HSI.
6. Study 6 - Iso_{BI} and Iso_{UNI} strength are both lower in players with acute HSI.

Chapter 2

Review of the Literature

The focus of this literature review is to;

1. Outline the anatomy of the hamstring musculature.
2. Detail the epidemiology and risk factors associated with HSI.
3. Discuss and describe muscle architecture as a modifiable risk factor.
4. Discuss concentric, eccentric and isometric strength and the various modes of hamstring testing.
5. Classify hamstring muscle injury and grading systems.
6. Discuss running and its relevance to HSI as it is the main mechanism of injury in GF.

The rationale for the research contained in studies 1-6 is discussed and outlined at the end of each section.

2.1 Anatomy

The hamstrings are composed of the posterior muscles of the thigh and include the biceps femoris long head (BFlh) and biceps femoris short head (BFsh), semi-membranous (SM) and semi-tendinosus (ST). They are biarticular in nature in that they both extend the hip and flex the knee (Chumanov et al., 2007). The BF and ST share a common tendon (Miller et al., 2007).

2.1.1 Origins

The origin comprises of the ischial tuberosity and extends laterally across the ischial bone with the BF and ST originating at the medial facet of the ischial tuberosity. A portion of the ST also originates on the inferior facet with the SM originating on the lateral facet (Figure 2.1) (Battermann et al., 2011). The SM, associated with the adductor magnus (AM) is separate to the conjoint tendons of the BF and ST however the origins of the hamstring musculature are interconnected as the SM and BF at the lateral aspect and deep portions of the ST are characterised by fibrous adhesions of varying extent (Battermann et al., 2011, Philippon et al., 2015). The BFsh originates from the lateral femur with a relatively small inter tendinous connection.

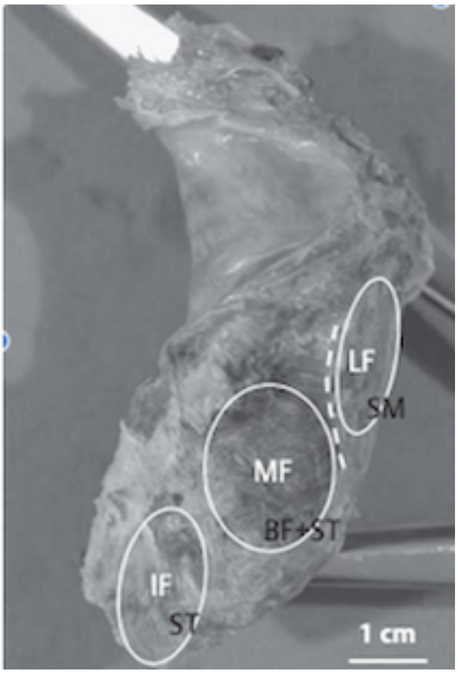
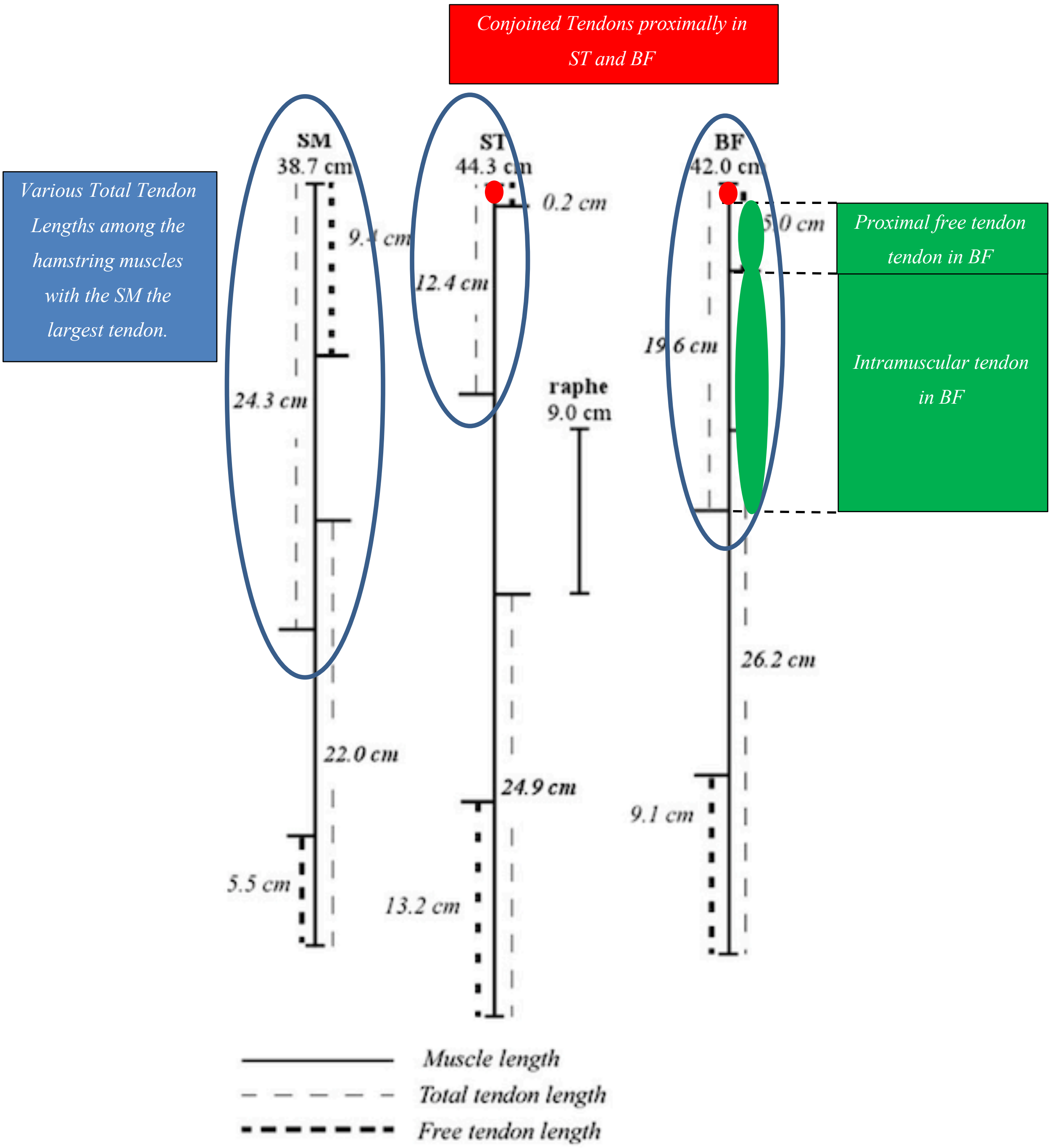


Figure 2. 1: *Hamstring origins*
(Battermann et al., 2011).
You will see the dorsal aspect of the right ischiac with the 3 origins for the Semi-tendinosus (ST), Biceps Femoris (BF) and Semi-tendinosus (ST) and Semi-membranosus (SM).

A round tendon at insertion, comprises the common head of the BFlh and ST at the medial facet, the majority of which is the BF tendon and a small portion of the ST which then flattens distally as it extends to adapt for the attachments of muscle fascicles of the ST (Battermann et al., 2011). The BFlh is further stabilised by the sacrotuberous ligament at the ischial tuberosity which may aid in tendon retraction during complete ruptures and also a retinaculum structure providing further stability across the ischial tuberosity (Bierry et al., 2014, Pérez-Bellmunt et al., 2015). The common tendon comprises on average 6.1cm^2 of the insertional mean surface area with the SM and ST comprising 4.1cm^2 and 2.0cm^2 respectively (Philippon et al., 2015).



Conjoined Tendons proximally in ST and BF

Various Total Tendon Lengths among the hamstring muscles with the SM the largest tendon.

Proximal free tendon tendon in BF

Intramuscular tendon in BF

Figure 2. 2: *Muscle and tendon lengths (Van der Made et al., 2013).*

2.1.2 Proximal Tendon Morphology

The muscle tendon unit is a composite structure composed of muscle, tendon, myotendinous junctions, tendon sheaths and tendon bone junctions. The most vulnerable part of muscle tendon bone unit is the muscle tendon junction as it transmits the force generated by the muscle fibres to the tendon and subsequently the force to the bone (El-Khoury et al., 1996). The SM is the most robust tendon with the greatest cross-sectional area (0.86cm^2), largest proximal tendon (31.9cm), free tendon (11.1cm) and also has the largest muscle tendon junction (20.8cm) (Woodley and Mercer, 2005b, Storey et al., 2016). The BFlh and ST separate 9-10cm distal to their origins and are not as robust with a cross sectional area of 0.47cm^2, proximal tendons of 27.1 and 12.9cm, proximal free tendons of 6.3 and 11.2cm and finally muscle tendon junction lengths of 20.6 and 11.7cm, respectively (Figure 2.2) (Woodley and Mercer, 2005a, Storey et al., 2016).

2.1.3 Muscle Characteristics

BFlh and SM are hemi pennate with parallel muscle fibers connecting proximal and distal regions (Kumazaki et al., 2012). ST is a fusiform shape and has longitudinal fibers interconnected by a tendinous septum. The BFlh is a slanted trapezoid muscle with longer fibers on the proximal side and shorter ones on the distal side (Figure 2.3) (Kumazaki et al., 2012).

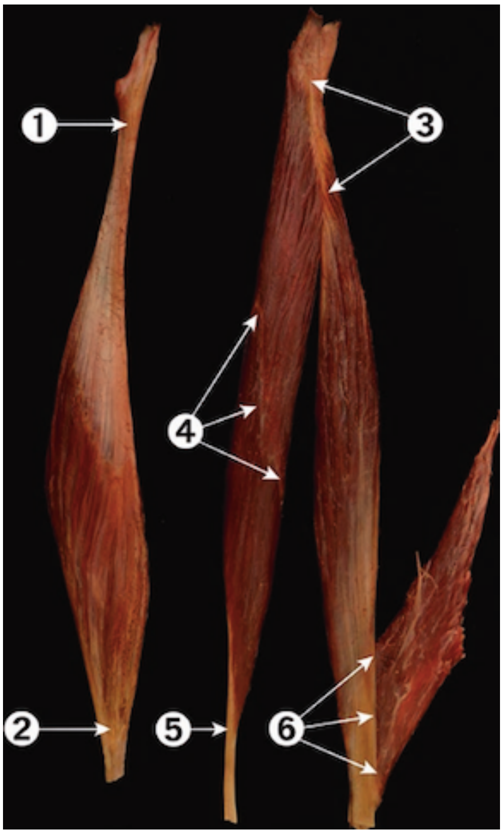


Figure 2. 3:*Hamstring anatomy*
(Timmins et al., 2020, Stępień et al., 2019).
(1) Proximal tendon of the SM muscle, (2) distal tendon of the SM muscle, (3) conjoined tendon of the ST and the BFlh, (4) tendinous inscription (raphe) of the ST muscle, (5) distal tendon of the ST muscle, (6) common distal tendon of the long and short head of the BF muscle.

2.1.4 Fascicle Length and Pennation

Fascicle (L_f) relates to the length of the muscle fascicles and is measured from the deep intramuscular tendon (aponeuroses) to the superficial tendon. Pennation angle (θ_p) is the angle at which these muscle fascicles attach to the aponeuroses (Timmins et al., 2016a). L_f influences the force-velocity curve and force length relationship (described in Figure 2.4) with previously injured muscles having shorter fascicles (Timmins et al., 2015, Bodine et al., 1982).

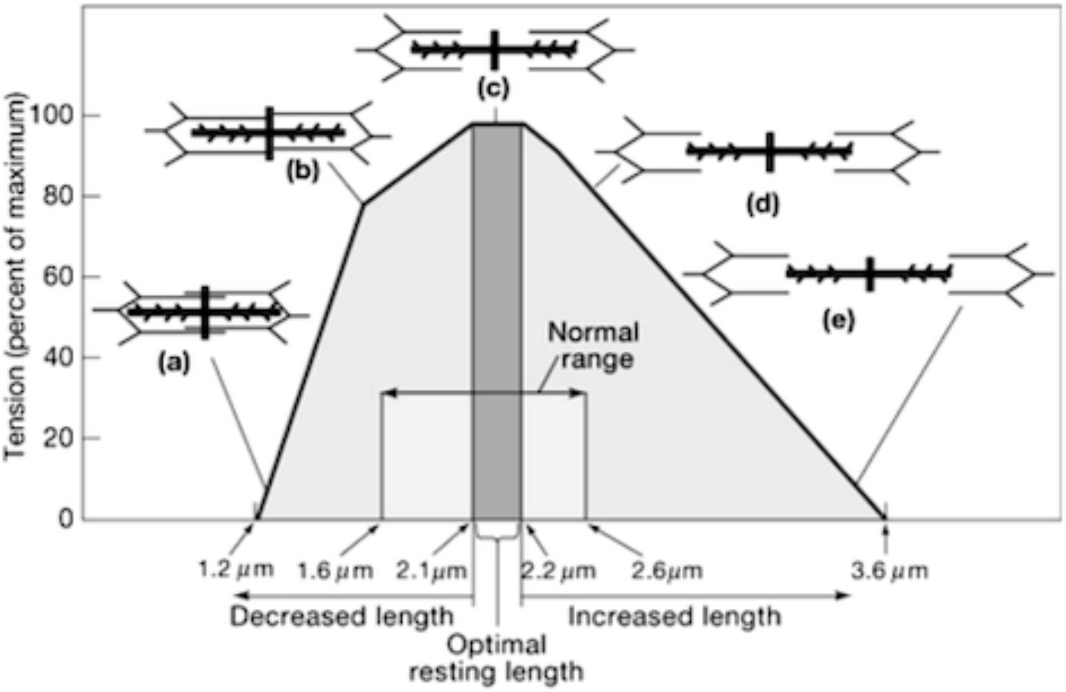


Figure 2. 4: *Sarcomere length tension relationship.*
(Power, 2012).
You will see to the left of the figure decreased length of the sarcomere which results in too much overlap between actin and myosin, while on the right side of the descending limb force is reduced as there is less/insufficient overlapping of the myofilaments. The result of which is a reduction in maximum force capacity outside of optimal resting length.

BFlh is pennate and the L_f can range between 5-14cm in both cadaveric and in-vivo analysis with θ_p ranging from 0-28^0, it has longer fascicles and greater pennation proximally in comparison to its mid and distal segments (Kellis et al., 2010, Delp et al., 1990, Potier et al., 2009, Blackburn et al., 2009). The BFsh has fascicles of 10.4-14cm in length and θ_p of 10-16^0 (Wickiewicz et al., 1983). BF L_f does not differ between sexes (Behan et al., 2018) and increases as we mature from 6.9cm to 7.6cm (13 yr olds v 15 yr olds) (Ritsche et al., 2020). If L_f were expressed relative to femur length this difference may not be as evident as increases in L_f maybe directly related to femur length with the possibility for taller athletes to have greater L_f.

2.2 Epidemiology and Risk Factors associated with HSI

2.2.1 Epidemiology

HSI is evident within all sports but particularly so within Gaelic Football (Brooks et al., 2006, Ekstrand et al., 2011, Orchard and Seward, 2010). An eight-year follow up of 307 players resulted in 391 HSI (Roe et al., 2016) and accounts for 12%-29% of all injuries in GF, 52% of all muscle injuries (Table 2.1) (Murphy et al., 2012, Newell et al., 2006, Roe et al., 2016, Roe et al., 2018b, Wilson et al., 2007, Blake et al., 2011, Cromwell et al., 2000). HSI within GF is more of an issue compared to other sports where it is 12% of all injuries in elite soccer, 15% in rugby union, 16%-17% in Australian Football and 17% in Hurling (Ekstrand et al., 2016, Orchard et al., 2013, Roe et al., 2016, Moore et al., 2015). The rate of injury to the lower limb in matches is high, 38.7 injuries /1000hrs and significantly higher than other body parts in which the rate of injury to the upper limb is 3.2 injuries per 1000hrs (Roe et al., 2018b). The situation is getting worse where a twofold increase in HSI from 2008/2011 to 2012/2015 has been reported (Roe et al., 2016). This is also the case in soccer where an annual average 2.3% increase in HSI over a 13-year period is seen (Ekstrand et al., 2016). Injury interventions as a result are having little if any, on injury rates (Goldman and Jones, 2010).

Table 2. 1 *The most common injuries within Gaelic football (Roe et al., 2016)***.**

All Injuries	**Match Play**	**Training**
Hamstring 23.9%	*Hamstring 23.1%*	*Hamstring 27.6%*
Groin 14.9%	Knee 12.7%	Groin 17.5%
Ankle 11.1%	Ankle 12.2%	Ankle 10.7%
Knee 11.1%	Groin 10.8%	Quadriceps 10.1%
Quadriceps 9.3%	Shoulder 9.7%	Knee 8.6%

The majority of HSI injuries occur during matches (64.4%) with less injuries at training (35.6%). The rate of injuries in matches (50-97 injuries per 1000 hours) is 7-13 times greater than those seen in training (2-6 injuries per 1000 hours) and reflect the competitive demands of match play (Table 2.1) (Murphy et al., 2012, Roe et al., 2016, Wilson et al., 2007, Blake et al., 2011). However, periodically during the season higher levels of hamstring injury can be seen in training at elite level. At elite level players spend large portions of the year without competitive games (1:8) resulting in longer training blocks and less exposure to matches and games (Roe et al., 2016).

The rate of HSI within the sport is concerning as it is 1.5-2.6 times higher than the rate of HSI sustained in professional soccer (4.77 & 0.51 injuries per 1000h) (Ekstrand et al., 2016), rugby (5.6 & 0.27 injuries per 1000h) (Brooks et al., 2006) and American football (2.7 & 0.47 injuries per 1000h) (Elliott et al., 2011). This represents a rate of 15-27 times and 7-20 times higher for matches and training in GF when compared to other sports. It is unclear in GF how the skills specific to GF such as kicking from the hand, hand passing and tackling affect these rates but maybe important factors relating to this increased incidence (Table 2.2).

Table 2.2: *Incidence of HSI/1000hrs in Training and Match play*

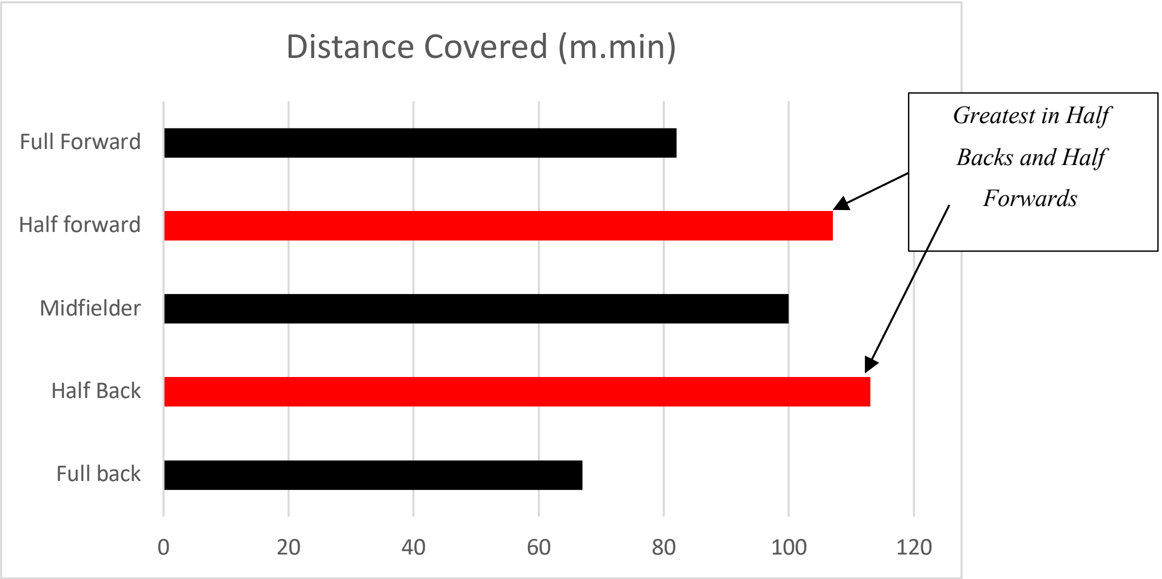
You will see the highest incidence is in GF.

Sport	**Training**	**Match Play**
Gaelic football (Roe et al., 2016)	*1.2*	*8.4*
Professional soccer (Ekstrand et al., 2016)	0.51	4.7
Rugby (Brooks et al., 2006)	0.27	5.6
American Football (Elliott et al., 2011)	0.47	2.7

Training load is high for an amateur sport, on average of 15 hours per week, 11 times more hours are spent training rather than in match-play (Murphy et al., 2012) with a training-match play ratio of 7.6 (Roe et al., 2016). Elite GF players train at a professional level as weekly training loads of 3475 ± 596 AU (rating of perceived exertion x training duration) are similar to those found in Australian rules football (Malone et al., 2017, Veugelers et al., 2016).

The majority of hamstring injuries are new (63.9%) however there is a high recurrence rate (36-47 %) (Roe et al., 2018b, O'Connor et al., 2017). The majority of recurrent injuries occur during match-play (59%) in comparison to training (36%) and are more common eight weeks following return to sport (Roe et al., 2018b). Recurrence of HSI in sport is widespread and it has been speculated in soccer as to whether injury rehab programs are effective (Hallén and Ekstrand, 2014) and train goads and volumes following return to training need to also be considered.

Non-contact injuries account for 73% of match-play injuries with 73% of all hamstring injuries occurring whilst running, sprinting (14%-26.8%), turning (12%), landing (7.1%) and kicking (4.5%) (Roe et al., 2018b, Wilson et al., 2007). Half backs and half forwards cover the greatest distances (Figure 2.1) which peak hamstring forces can range between 2,880N-4,160N and negative work range between 112-208J for a 80kg athlete when running at 80-100% of maximal speed (Chumanov et al., 2007). The level of HSI within the sport can be attributed to the fact that players are expected to cover large distances during games. Moreover, GF players are categorised into defenders, midfielders and forwards according to their playing role within the team. Elite players cover on average 132m.min^{-1} which can increase to 230 m.min^{-1} (Malone et al., 2017) and distances of 5,417±425m, with 924.4±225m ≥17km/h or at high-speed distance (Malone et al., 2017). Midfielders have the greatest work rate profiles, however more recently forwards and defenders were subdivided into half backs and half forwards which indicated a similar and in some cases greater work rate profile than midfielders (Figure 2.5) (Gamble et al., 2019). This is reflective of a trend in which defender’s and midfielders are 1-2 times more likely to develop HSI compared to their forward counterparts (Roe et al., 2016).



Greatest in Half Backs and Half Forwards

Figure 2. 5: *Distance covered according to playing position (Gamble et al., 2019a).*

The majority of HSI are to the BF (44.1%) and to the proximal region (Roe et al., 2016). Similarly, elite English soccer players have also reported more injuries to the BF (53%) compared to ST (16%) and SM (13%) (Woods et al., 2002). There are a number of variations within the hamstring musculature which predispose the BF to injury and this is discussed in more detail later in the chapter.

Acute (77%) injuries are more common than chronic or overuse injuries (16%) (Roe et al., 2016) and these result (in 26 days’) loss, between 8-28 days and teams typically experience 9 hamstring injuries a season resulting in 299 time-loss days per team (Roe et al., 2018b). The average time loss in soccer is 19.7 days per 1000h exposure with match play injuries causing the greatest time loss in comparison to injuries sustained whilst training (88.5 vs 6.3 injury days absence/1000h exposure) (Ekstrand et al., 2016). Time loss is due to the severity of injury as the average time loss according to grade is 17+/- 10 days for Grade I, 22+/-11 days for Grade II and 73+/- 60 days for Grade III (large variability in the literature when returning players from high grade hamstring injuries) (Mueller-Wohlfahrt et al., 2013).

HSI is greater in those aged 18-20 years and >30 years, middle aged groups have a lower injury incidence and players who sustain an injury are 3 times more likely to sustain future HSI (Roe et al., 2016). In GF adolescent football players have slightly higher incidence of match and training injury with rates of 9 and 3 injuries per 1000hrs for match and training respectively (O'Connor et al., 2017). Younger players are at a period in their careers in which exposure to training loads and particularly training volume coupled with the effects of maturation may predispose them to injury while at the other end of the spectrum older players may be more susceptible to HSI due to degeneration of the lumbar spine and also given the fact that GAA is amateur game whereby players are required to work full time very often before and directly after training sessions. Work commitments and hence time management in which recovery strategies should be implemented can often be very challenging and sometimes even overlooked altogether.

Playing level is also important to consider and at sub-elite level HSI is not as prevalent as those participating at elite level and reflective of the playing standard in which the exposure to games and training is not as high as elite players (Wilson et al., 2007). The elite season in GF is split into a pre-season (January) and competitive season (February-September) with 17% of hamstring injuries occurring in pre-season (approximately 7 weeks) and 64% during the competition season (Roe et al., 2016). Preseason training is particularly important as players that are not exposed to sufficient preseason eccentric hamstring strength are 2.7 times more likely to sustain an injury during the season (Opar et al., 2015). Ineffective pre-season conditioning may impair player's competitive readiness, thereby increasing injury risk during the playing season and returning from offseason very often when players have deconditioned may make them further susceptible to injury (Elliott et al., 2011). On the other hand, over exposure is also a contributing factor to HSI for particular players. The sub-elite season generally runs from February to November or December and a pre-season is not as well defined, while elite players are also expected to participate at sub-elite level following elimination or completion of their elite season, therefore reducing their "out of season" recovery period. This can potentially increase the risk of injury in which there are many factors associated with HSI.

2.2.2 Risk factors associated with HSI

Risk factors for HSI can be classified as extrinsic (sport, load, environment, climate) or intrinsic (factors relating to the player). Intrinsic risk factors have received greater research as these can be further categorised into modifiable (those factors associated with the player can be changed) and non-modifiable (factors associated with a player that do not change). Modifiable risk factors have been widely researched in an attempt to lessen the risk of injury and in particular, injury burden on players.

Age, previous HSI injury, other injuries, playing position (non-modifiable risk factors) have been associated with the risk of HSI. In a recent 7 year review of HSI (71,324 athletes) older players (RR=1.6, p=0.002), previous HSI (RR=2.7, p<0.001), previous ACL (RR=1.7, p=0.002) and calf injury (RR=1.5, p<0.001) are the strongest non-modifiable risk factors (Figure 2.8). In Gaelic football players over 30 years of age are at greatest risk of injury (Dekkers et al., 2022). It has been proposed that altering muscle architecture (Lieber and Fridén, 2000), fibre type (Lexell, 1993) increases in stiffness and reducing neurological function (Doherty et al., 1993) are all influence's on muscle function as athletes get older. Age is an important non-modifiable risk factor as it directly effects a number of modifiable risk factors as outlined in Figure 2.7. Furthermore, it has been reported that strength, power and running capacity decreases as we get older (Faulkner et al., 2008). Previous HSI has been reported to increase future risk of injury by 2.7-3.7 times and can also carry over to the following season (Smith et al., 2021, Green et al., 2020). Previous calf and ACL injury are also both seen to increase the risk of HSI by 1.7 and 1.5 times, respectively (Green et al., 2020). It is widely accepted that these elevations in HSI risk associated with previous injuries are related to compensations and thus overloading of specific areas of the kinetic chain or also can be directly linked to deficits in strength. Playing position has been linked to HSI with particular emphasis on the frequency of kicking (Whiteley et al., 2017) and in particular the exposure to high speed running (Brooks and Kemp, 2011).

Modifiable risk factors are not as strongly linked to HSI but have widely been studied as screening and intervention programs attempt to address these specific risk factors, intrinsic to each player (Figure 2.6). The two most widely researched are strength and flexibility/mobility of players where reduced hamstring strength and in particular eccentric and isometric strength, have all been associated with an increased risk of HSI (Green et al., 2022). Eccentric strength (Maniar et al., 2016) during the Nordic hamstring exercise (Timmins et al., 2016b) and also eccentric strength during IKD measurement has been reported to be lower in players following HSI (Green and Pizzari, 2017). Isometric strength has also has been associated with HSI, with deficits existing in previously injured players (Yamamoto, 1993). Eccentric strength training can reduce the incidence of HSI by 56.8-70% by 1) addressing functional hamstrings/quadriceps ratio and 2) by reducing any underling asymmetries (Rudisill et al., 2022). Mobility and flexibility on the other hand is not as sensitive to HSI as the AKE (active knee extension) test, as a function of hamstring flexibility, has been shown to have little sensitivity to HSI in Gaelic football (O'Connor et al., 2019).

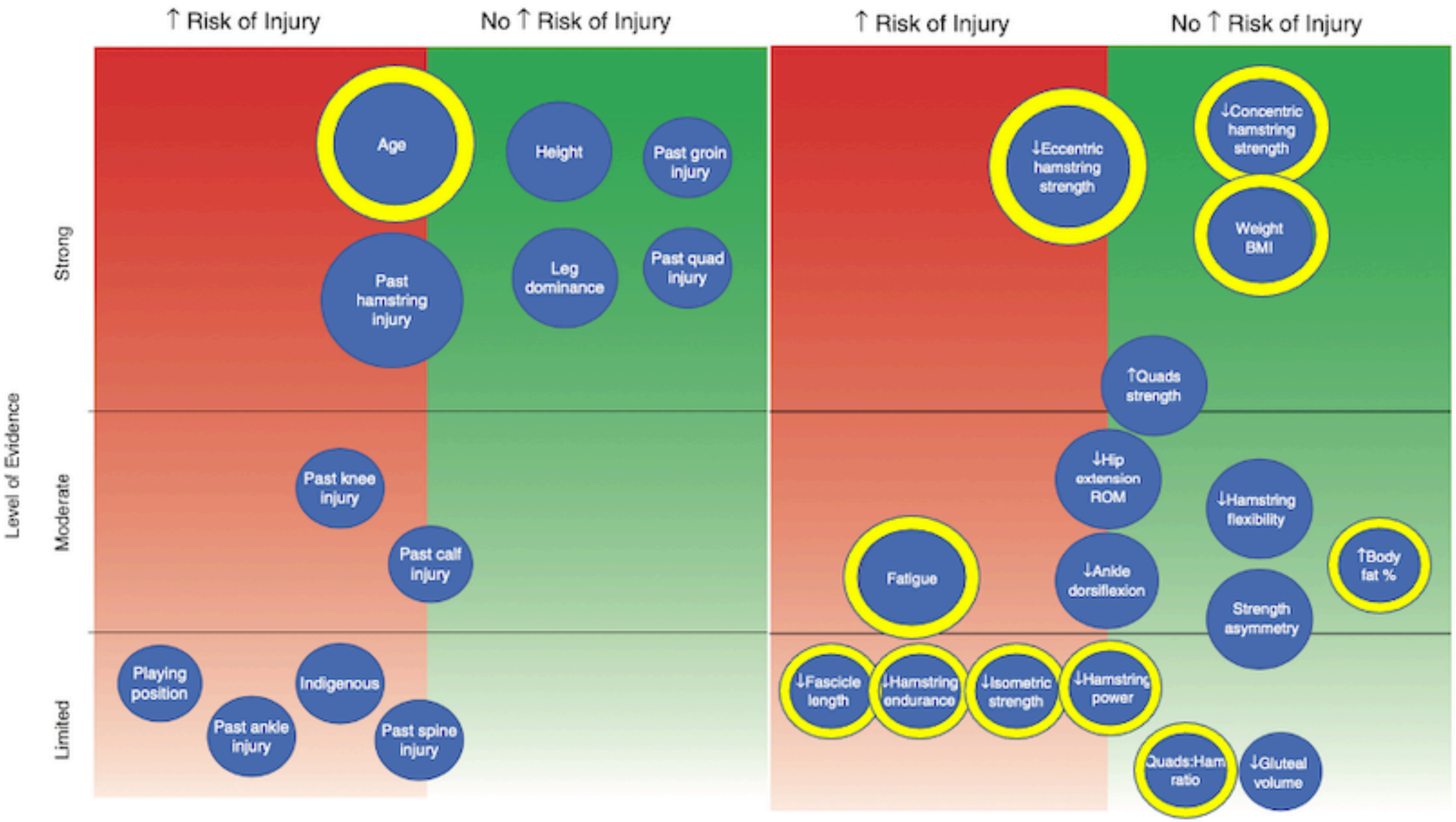


Figure 2. 6: *Non-modifiable (Left hand side) and modifiable (Right hand side) risk factors and their level of evidence (Modified from Thorborg et al. (2020))*

You will see age highlighted to the top left where it interacts with a number of modifiable risk factors.

Other modifiable risk factors involve 1) power and ballistic function, where decreases in the countermovement jump (Venturelli et al., 2011) 2) biceps femoris muscle activity, where reductions in muscle activity and neuromuscular function in the posterior chain (Schuermans et al., 2017) 3) muscle fatigue during where eccentric (Greco et al., 2013), where isometric (Robineau et al., 2012) and concentric (Marshall et al., 2014) strength decreases following match play, have all been postulated to be associated with HSI. It is important players have adequate power, muscle endurance and ballistic function to tolerate the stresses of match play (Dye, 1996).

In the last few years running technique has also been researched in more detail, in which increases in pelvic tilt, ipsilateral trunk rotation, reduced range of hip motion, overstriding, reduced biceps femoris activity are all associated with HSI (Franettovich, 2017, Schuermans et al., 2017, Small et al., 2009, Daly et al., 2016, Timmins et al., 2014). Altered or ineffective technique (in which the hamstrings are overloaded or exposed in more vulnerable positions) and high speed running volume (in which players are exposed to large increases in high speed running) can increase the risk of HSI (OR=6.44, 95% CI 2.99 to 14.1, $p<0.001$) (Duhig et al., 2016). Running speeds and volumes are particularly important for the management of HSI as running exposure accounts for 43% of the variability in Lf, while managing high velocity running exposure and eccentric strength together allows for 90% of the controllable determinants in fascicle length (McGrath et al., 2020). These modifiable risk factors have been applied in screening models and are mainly undertaken in pre-season to tailor individualised programs, specific to each player. A study by Lahti and colleagues (2020) conducted a multifactorial screening program where individualised training programs were prescribed for lumbo-pelvic control, range of motion, posterior chain strength, sprint mechanics (Figure 2.7). The study demonstrated the importance of individualised training programs based off a multifactorial screening program but it was inconclusive as to the reductions for HSI.

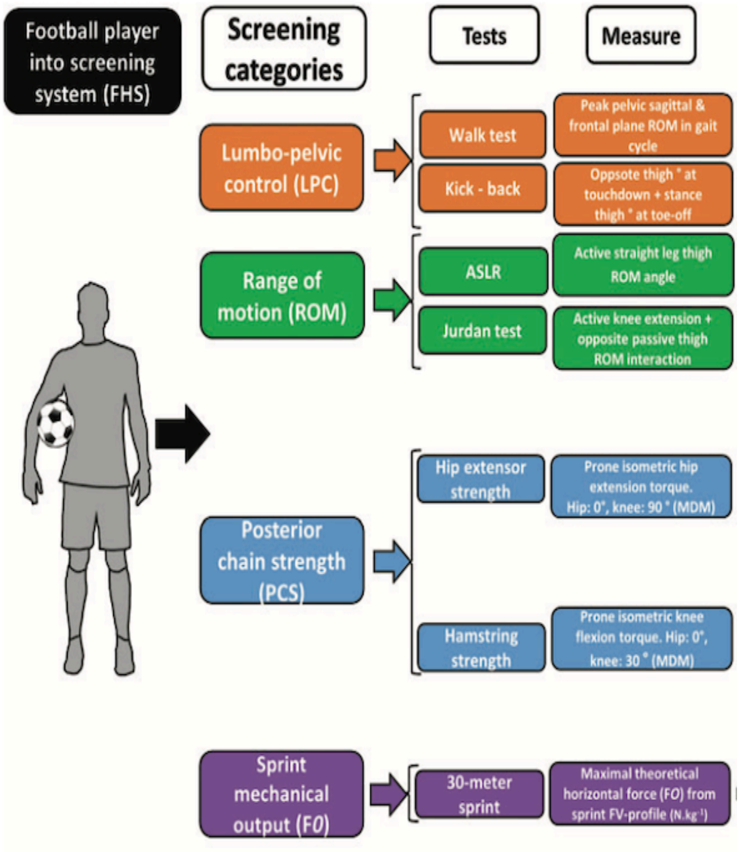


Figure 2. 7:*Multifactorial screening program for hamstring strain injury (Lahti et al., 2020).*

You will see Hamstring strength as one of 7 areas prioritised in a screening system for HSI.

2.2.3 Conclusions and Future Research

HSI within GF is the most common injury in the sport and an issue in which there is (1) a higher incidence and rate of injury than other field sports and (2) a high recurrence rate. There are a number of risk factors and hamstring architecture and strength are strong modifiable risk factors which have been shown to reduce HSI.

2.3 Morphology, Architecture and Injury Risk

2.3.1 Proximal tendon

The proximal portion of the muscle is vulnerable to injury as it has a unique configuration where the tendons of the BFlh and the ST tendons divide into individual tendons approximately 9.1-9.9cm from the ischial tuberosity (Garrett et al., 1988, Van der Made et al., 2013). Given that both these muscles are required to tolerate large forces during explosive activities it is unclear as to the effect of the stress and strain on these individual tendons and whether this has a direct link to injury at this site. Each hamstring has various architectural differences in relation to the muscle tendon bone unit. The BFsh (28.5cm-29.1cm) has the shortest muscle tendon unit (MTU) with the ST (44.3cm-47.5cm) displaying the longest MTU with the BFlh (38.9cm-42.0cm) and the SM (38.7cm-40.4cm) (Woodley and Mercer, 2005b, Kellis et al., 2012, van der Made et al., 2015). These MTU and the proximal splitting of the BFlh/ST possibly predispose this area to injury.

Proximal tendon units are required to tolerate stresses and workloads during sprinting and kicking, and they therefore require elastic capabilities to extend and shorten. Whilst kicking and sprinting players are required to flex their hip and this hip flexion produces a more pronounced stretch in the ST followed by the BFlh and then the SM. When the hip flexes and the knee extends rapidly the ST and BFlh lengthen slightly more than the SM however during terminal swing the BFlh experiences less shortening than the other muscles (Thelen et al., 2005b). The strain upon BFlh distal tendon/aponeurosis increases by 14.6% and it becomes highly stretched during passive knee extension which is facilitated by its unique muscle architecture in which it is shorter and more pennated (Kellis et al., 2016). This change in length, varies within the hamstring group with the BFlh undergoing a 11-14.7% change in length relative to resting values (Kumazaki et al., 2012). The effect of hip flexion on the change in length of the BFlh has been debated, in cadavers this change could be as high as 30% (Visser et al., 1990) but in vivo analysis suggests a lower value of 13% (Kellis, 2018). This 13-30% in BFlh change in length places it in a lengthened vulnerable state.

Peak muscle forces occur adjacent to the proximal aponeurosis (Fiorentino and Blemker, 2014). This is due to stretching of the muscle tissue surrounding the MTU to accommodate the greater stress in this region and also due to the larger cross-sectional area converging from the middle of the muscle into the proximal MTU. Maximum tendon/aponeurosis strain has been measured by ultrasound and digitising a fascicle and aponeurosis. Strain is calculated by dividing the displacement of the fascicle under maximum isometric contraction (prone on a IKD) by its resting length and is reported to increase by 71%, 19% and 27% at 0°, 45° and 90° (Kellis et al., 2016). This has implications for the mechanism of HSI as injury occurs in long lever positions. To even compound this predicament larger proximal tendon/aponeurosis results in an increase in force transfer (Biewener and Roberts, 2000) and as a result this reduces the ability to stretch which may in turn increase the risk for potential re-injury (Fletcher et al., 2010).

Longer tendons result in greater excursion capacity and greater compliance, a tendon with greater CSA results in higher levels of stiffness. Stiffer tendons can also transfer more force before the point of failure, however more compliant tendons result in the muscle fascicles shortening, to take up the excess compliance in the tendons (Thelen et al., 2006). The BFlh displays the greatest levels of stiffness in knee flexion and hip flexion in comparison to both the SM and the ST and exhibits the greatest resistance to stretch during a typical hamstring stretch (Magnusson et al., 2000). Yet it is required to tolerate the largest strain of all the hamstrings in its most lengthened position.

It is clear all these unique architectural traits of the BFlh contribute to the high level of incidence in the muscle. Identification of this underlying morphology requires well-resourced, high-powered imaging (which is expensive) and very experienced technicians. The surrounding architecture involving fascicle length and pennation is not as difficult to determine, is more accessible due to advances in scanning techniques and can also be an important consideration in HSI risk.

2.3.2 Bicep Femoris Fascicle length

Players with previous HSI have shorter BFlh L_f than those who remain uninjured (<10.56cm) and have a four-fold increased risk of injury as a result (Timmins et al., 2015). BFlh L_f are shorter in previously injured muscles when compared to the non-injured side (Timmins et al., 2015). Shorter L_f with fewer in series sarcomeres maybe more susceptible to being overstretched by powerful eccentric contractions (Brockett et al., 2004). It is also accepted that shorter L_f in the biceps femoris predispose it to injury as it has less elastic capability or potential for stretching during powerful eccentric contractions due to the force length relationship (Figure 2.6) (Potier et al., 2009).

Interestingly L_f characteristics throughout the hamstring muscle are not the same as regions or compartments from the proximal to distal segment had various degrees of L_f. Proximal L_f are 38% longer than distal L_f in a resting condition, while in an activated position, proximal L_f were still longer by 33% (Bennett et al., 2014). Proximally there is 1.5 times greater strain on the aponeurosis during eccentric contractions and there are 2 times greater fascicle strain in comparison to distal segments (Bennett et al., 2014). This greater level of strain and change in proximal L_f is required to facilitate the change in muscle length and tolerate eccentric contraction and may help explain why this specific difference exists in morphology when comparing proximal and distal segments.

2.3.3 Bicep Femoris Pennation

Greater θ_p indicates a greater number of fascicles are packed into the muscle, parallel to each other in an attempt to increase force production (Aagaard et al., 2001, Azizi and Roberts, 2014, Astrand et al., 1986). θ_p reported in the literature for the BFlh range from 0 to 28^0 (Kellis, 2018). This variability in the literature can be attributed to the different areas of the muscle that has been measured, the joint position, in vivo and cadaver studies.

Similarly as with L_f, θ_p within the muscle is compartmentalised with the BFlh having greater pennation proximally ($9.3 +/- 2.2^0$) than distally ($12.3+/-3.8^0$) (Kellis et al., 2010) (Tosovic et al., 2016). Other areas are in line with the tendon to allow greater efficiency of force transfer (Scott et al., 1993). The differences in θ_p of the muscle allows regions with greater pennation to produce greater force. It is likely that its proximal segment is better suited for force production in comparison to the more distal segments.

Following injury it has been reported that θ_p underneath the muscle scar and site of injury showed a decrease of 51.4% and this was present 1 year after injury with very minor changes in the unaffected area (Kellis et al., 2016) which may also have a direct effect on the large incidence of re-injury within the sport.

Given the combination of longer L_f and greater θ_p proximally it would suggest that there is an increased emphasis on the proximal segment for lengthening and force production. It is unclear as how this affects Gaelic footballers, as this has not previously been reported within the sport.

2.3.4 Architectural Changes

Strength training has been advocated widely as a preventative measure for hamstring injury and architectural changes in both L_f and θ_p have been associated with resistance training (Bourne et al., 2017). Eccentric strength training in particular is effective, as it increases L_f and reduces θ_p (Timmins et al., 2015). Significant increases in L_f of 16-34% have been reported for training programs of 6-8 weeks (Timmins et al., 2016a, Potier et al., 2009, Alonso-Fernandez et al., 2018). Nordic hamstring exercise programs have elicited increases in L_f from 10.6cm to 12.8cm (Bourne et al., 2016). This increase in L_f is important as this allows the muscle to stretch and elongate through excessive ranges and the probability of injury is reduced by 74% for every 0.5cm increase in L_f (Timmins et al., 2015).

Interestingly sprint training (16%) elicits greater adaptations in L_f in comparison to Nordic strengthening (7%) when added to soccer training (Brughelli et al., 2010). This may indicate exposure to running programs specific to the football code has preventative measures for HSI. In particular, chronic running loads >80% of maximum velocity account for 43% of the variability in L_f changes whereas running speeds over 90% of max velocity are insignificant (McGrath et al., 2020). It is unclear in Gaelic football as to the training related L_f adaptation to the training load and strength programming and how this directly relates to hamstring strength within the sport and its relevance for prevention of HSI.

HSI can occur at various times throughout the playing season and it is noteworthy that elite Australian footballers with a history of HSI, had shorter L_f at the end of the season compared to the start in both their injured and injured limbs (Timmins et al., 2017). This is directly related to the training stimulus in which the adaptation to L_f is only temporary. An 8-week

Nordic hamstring strengthening protocol and a 4-week detraining period resulted in a significant increase in L_f during the training period and a significant decrease during the de-training period (Alonso-Fernandez et al., 2018). Furthermore, the de-training effect for BFlh L_f following eccentric training interventions were found to be as little as 4 weeks and L_f training adaptations were reversed after 28 days of detraining (Timmins et al., 2015). Given this research it is necessary to track muscle architecture throughout the playing season and no study to date has a record of L_f during the off season or pre-season period. There is also no research available on match and training exposure and what consequence these loads have on L_f throughout the season, which maybe beyond the scope of this thesis.

It is also important to consider the stimulus for L_f training adaptations as L_f is more sensitive to a training response from hip position than knee positions (Hawkins and Hull, 1990). This is believed to occur from a greater moment arm and therefore greater hamstring muscle forces to elicit a response (Visser et al., 1990). Training the muscle in longer rather than shorter muscle lengths, in outer range induces L_f adaptations (Sharifnezhad et al., 2014). These adaptations of L_f to eccentric training are generally reported to result from an increase in series sacromeres as has been previously reported during downhill running of vastus intermedius of rats during a 5-week programme (Potier et al., 2009, Lynn and Morgan, 1994). A combination of sarcomerogenesis (formation and development of sacromeres), in series sarcomeres (Proske and Morgan, 2001) and increases in tendon stiffness (Butterfield and Herzog, 2005), adaptations due to the induced muscle damage during the nordic hamstring exercise (NHE) allow the hamstrings to stretch further. This has been seen to shift the torque curve towards longer lengths. It has been suggested that this may help reduce HSI risk during the terminal phase of running, although plausible but also controversial as there is no direct evidence to indicate as to whether this is directly the case.

The relationship of eccentric strength and L_f in both the BFlh and SM has also been examined in-season in a cohort of elite U19 soccer players in which L_f was measured via EFOV and eccentric hamstring strength via the nordbord (ECC_{NB}) (Buchheit et al., 2016). Interestingly, they examined the data in a two-dimensional mode with respect to four quadrants with players categorised into a high-risk quadrant "quadrant of doom" which contained players with both shorter L_f and below average eccentric strength. On the other hand, players in the upper left quadrant were seen to be at lower risk with longer L_f and above average levels of ECC_{NB} (Figure 2.8).

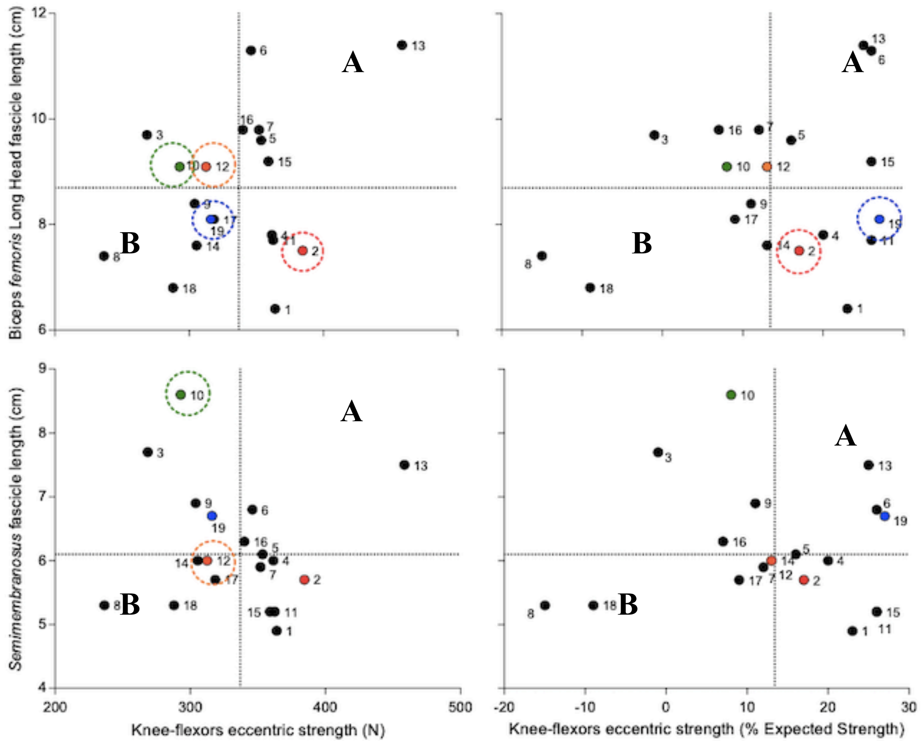


Figure 2. 8: *Lf of the Biceps femoris long head and Semimembranosus and knee flexor strength during the* NB_{ECC} *(Buchheit et al., 2019).*

A – lower risk quadrant with longer L_f *and above average* NB_{ECC} *strength; B – 'Quadrant of doom" – shorter* L_f *and below average* NB_{ECC} *strength.*

Changes in θ_p also have been directly reported to type of strength training and directly related to the stimuli, eccentric training decreases θ_p, and concentric training increases θ_p (Timmins et al., 2015). θ_p has been found to increase following 4 weeks of detraining (Timmins et al., 2016a). Nordic hamstring strengthening post training in soccer players also has a hypertrophic effect on the BF by increasing muscle CSA and θ_p (10%) (Brughelli et al., 2010). Whilst these changes in θ_p may be related to each individual muscle, it may be possible that changes in θ_p are reliant on the extent of hypertrophy (Potier et al., 2009). Again, longitudinal follow up of θ_p would help to determine its relationship to proximal hamstring injury and highlight de-training periods throughout the playing season, which may predispose players to mid-season injury.

2.3.5 Measurement

L_f and θ_p have both been calculated from cadavers and also more commonly with ultrasound measurement. This is undertaken by estimating L_f in one of three main methods L_f 1) a manual extrapolation method (Potier et al., 2009), 2) a method used to determine vastus lateralis applied to the BFlh (Blazevich et al., 2006) and 3) a method in which the non-visible portion of the fascicle is extrapolated (Finni et al., 2001). Direct determination by measuring the whole fascicle are more accurate by EFOV in which the whole muscle is scanned (Pimenta et al., 2018). Estimated methods using trigonometric equations tend to overestimate but also on occasions underestimates L_f and is also athlete dependant (Noorkoiv et al., 2010, Franchi et al., 2019). Furthermore, imaging is localised to 4-5cm and fascicles when resting are 30-50% of total length and estimation and extension of this data by up to 50% is required (Franchi et al., 2018), whereas EFOV directly measures whole fascicles. With these limitations in mind data existing in the literature to date is slightly over estimating the effect of eccentric training on L_f as studies involving trigonometric equations report an increase in L_f between 13-24% whereas changes in L_f when using EFOV are not as large, 4.5-4.8% (Lacome et al., 2019). EFOV has also been shown to the closest measurement when compared to cadaveric studies (Franchi et al., 2019). These anomalies in L_f determination are particularly problematic when comparing the effects of training induced changes in fascicle length. With this in mind it would be worth expanding the research base on EFOV to directly determine fascicle length and pennation.

2.3.6 Conclusions & Future Research

With peak muscle forces occurring proximally, stiffness of the MTU and the potential for injury, it is clear that the underlying L_f and θ_p may be directly linked to HSI. Investigation of which, would provide some useful insight into the surrounding debate and may even highlight players at risk of HSI. Direct determination of L_f and θ_p is important due to anomalies associated with estimated methods. There is a distinct lack of knowledge on L_f and θ_p and its relationship to HSI and has not been previously researched in GF.

2.4 Eccentric Strength and HSI

Strength is another strong modifiable risk factor and in particular eccentric strength which has been assessed both in the form of IKD and NB_{Ecc}. The first studies on Isokinetic dynamometry attempted to assess the strength of the hamstrings (Burkett, 1970, Heiser et al., 1984) and more recent studies have attempted to predict and define the risk of HSI in sport (Croisier et al., 2002, Lee et al., 2009). Concentric and eccentric strength at various speeds of movement (30°/s-500°/s) have been assessed and various ratios created to analyse the data in relation to HSI risk and prevention (Yeung et al., 2009). These ratios have included hamstring to contra-lateral hamstring ratios, conventional, functional and mixed ratios and defined later in this chapter. Another area of consideration in relation to isokinetics is methodology as there has been much debate in the literature around the validity, reliability and error of measurement associated with IKD measurement and its application to hamstring (Baltzopoulos et al., 2012, Drouin et al., 2004, Kaufman et al., 1995, Thompson et al., 2018).

2.4.1 Peak torque and Hamstring to opposite Hamstring ratios

Peak torque (PT) is a measure of force acting about a joint axis, during which lower levels of eccentric knee torque have been reported to elevate the risk of future HSI (Bourne et al., 2017). During pre-season a reduced hamstring eccentric peak torque at 30^0/s <2.44 times body weight (e.g 80 kg male = <195N) is associated with almost six-fold increase in the risk of HSI in professional footballers (Lee et al., 2018). The between limb imbalances or hamstring-to-opposite hamstring (H_{opp}:H_{opp}) is the relationship of hamstring muscle to either the dominant or injured/involved side. It is reported that in professional soccer players this differs significantly in injured versus uninjured players for concentric H_{opp60}:H_{opp60} (0.9+/-0.07 v 1.05+/-0.1) and eccentric strength (0.79+/-0.23 v 0.94 +/-0.15) with a cut off of 0.90 at 60^0/s recommended for HSI prevention (Orchard et al., 1997). Isokinetic eccentric knee flexor torque ≥15% increased the risk of hamstring injury fourfold (95% CI 1.13-13.23) among elite soccer players (Fousekis et al., 2011) and there are also significant deficits in eccentric knee flexor following injury (95% CI 0.04-0.37 Nm/kg^{-1}) (Sugiura et al., 2008). Furthermore, lower eccentric strength at 30°/s and 120°/s for previously injured athletes has moderate evidence across 4 studies (Croisier and Crielaard, 2000, Croisier et al., 2002, Jönhagen et al., 1994, Mackey et al., 2011) whereas high velocity measures of 240°/s and 300°/s have limited evidence (Lee et al., 2009, Jönhagen et al., 1994). H_{opp}:H_{opp} is important as at high speed the accumulated increase in negative work done and increases in neuromuscular control can create stride to stride variations which over repeated strides at high speed may result in accumulated overstretching of sacromeres that predispose the muscle to injury (Chumanov et al., 2007).

2.4.2 Conventional ratio

The conventional hamstring to quadriceps ratio (H_{con}/Q_{con}) was first introduced by Hislop and Perrine (1967) and is calculated by dividing the maximal peak torque of the hamstring during concentric knee flexion by the maximal peak torque of the quadriceps during concentric knee extension. It has been hypothesised that this particular ratio assesses the ability of the agonist (quadriceps) to the antagonist (hamstrings) musculature in co-contracting and braking the agonist (Wilk et al., 1994). This could have potential application for the transition phase of late swing to early stance in which the hamstrings are required to work eccentrically and possibly co-contract as the quadriceps reaches peak EMG levels. An increase in quadriceps activation levels occurs during the last 12% of the swing phase in co-contracting with the hamstrings in decelerating the limb for ground contact (Wyatt and Edwards, 1981). As the quadriceps is a larger muscle group it could be proposed that inadequate hamstring strength relative to the quadriceps could predispose it to injury during co-contraction (Heiser et al., 1984, Knapik et al., 1991, Orchard et al., 1997, Sugiura et al., 2008, Yamamoto, 1993).

In Table 2.3 it is evident that conventional ratios vary within the literature between 50-80% and are dependent on the speed of IKD testing (Kannus, 1994, Baroni et al., 2020). It has been proposed that a specific torque-velocity relationship exists in which the hamstrings have a greater capacity to generate strength than the quadriceps at increased isokinetic velocities (Hewett et al., 2008), although one would assume this may be training and sport dependant.

Table 2. 3: *Conventional ratios and various angular velocities of IKD (Baroni et al., 2020).*
The trend is for these ratios to increase with an increase in angular velocity.

Speed (°/s)	H_{con}/Q_{con}
12	0.52 +/- 0.07
30	0.52 +/- 0.08
60	0.65 +/- 0.12
90	0.57 +/- 0.06
120	0.65 +/- 0.16
180	0.67 +/- 0.17
240	0.80 +/- 0.40
300	0.70 +/- 0.15
360	0.80 +/- 0.13

A cut off point of 0.60 for HSI has been widely accepted at 60°/s and 0.65 at 180°/s has been reported but not commonly used (Heiser et al., 1984). More recently these ratios have been refined and examined in respect of HSI risk and at 60°/s a ratio <0.66 was found to significantly increase the risk of hamstring strain over the proceeding 2 years in Australian rules footballers (Cameron et al., 2003). It has also been reported in pre-season ratio <0.50 increases the risk of hamstring injury 3-fold in professional soccer players and also in Brazilian professional soccer players (0.55-0.65 by 8-45 times) (Liporaci et al., 2019, Lee and Kim, 2017). At 180°/s the ratio is reported at 0.67+/-0.17 (Higashihara et al., 2018) where a ratio <0.6 significantly increased the risk of hamstring injury, 17 times (Yeung et al., 2014). Testing at 60°/s has been recommended for conventional ratios to minimise the risk of injury as small effect sizes (limited practical application) have been reported for H_{con60}/Q_{con60} (-0.32; 95%CI -0.54- -0.11;I^2=0%) and H_{con120}/Q_{con120} (-0.43; 95%CI -0.83- -0.03;I^2=0%) but not at faster speeds of H_{con180}/Q_{con180} and H_{con240}/Q_{con240} (Maniar et al., 2016). However these ratios are sport dependant and sports involving different demands should not utilise the same ratio thresholds (Yeung et al., 2014) (Magalhães et al., 2004), although one would need to consider the speed of testing and its error of measurement. The conventional ratio increases with angular velocity and the hamstrings becomes more eficent at producing force relative to quadricpes (Quadricpes function declines with increasing anguler velocity above 180°/s).

2.4.3 Functional Ratio

The functional ratio (fH:Q) was first introduced by Dvir et al. (1989). This is calculated by dividing eccentric maximal peak torque of the hamstrings by maximal concentric peak torque of the quadriceps (Aagaard et al., 1995). It is more specific in determining the ability of the eccentrically acting hamstring to brake the action of the concentrically contracting quadriceps during the late swing phase of the gait cycle (Yeung et al., 2009) (Figure 2.9).

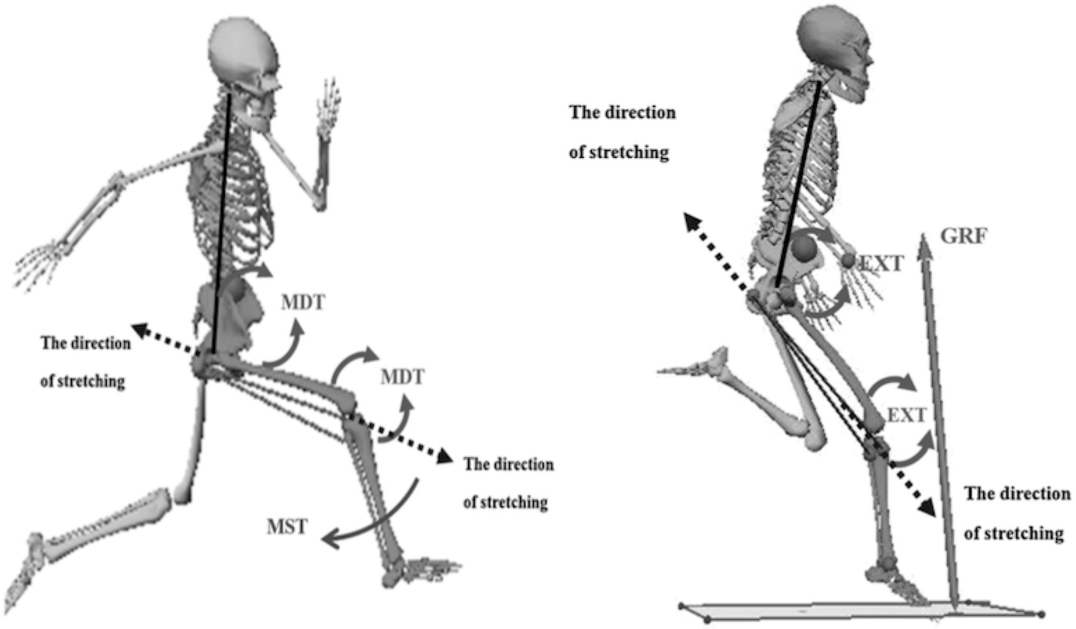


Figure 2. 9: *Joint torques at the hip and knee in late swing and early stance (Sun et al., 2015).*
During which the hamstrings is forced to actively lengthen illustrated by the direction of stretching (MDT inertial loads, MST muscle torque, GRF Ground reaction force).

Specifically during the late swing and initial stance phases, as the hamstrings acts eccentrically due to the large passive forces about the hip and knee joint (Sun et al., 2015). This more accurately reflects and mirrors the force-length and force velocity characteristics of the agonist/antagonist and takes into account the specific eccentric contraction of the hamstrings during co-contraction with the quadriceps. The role of the quadriceps is detailed in Figure 2.10 (Yeung et al., 2009).

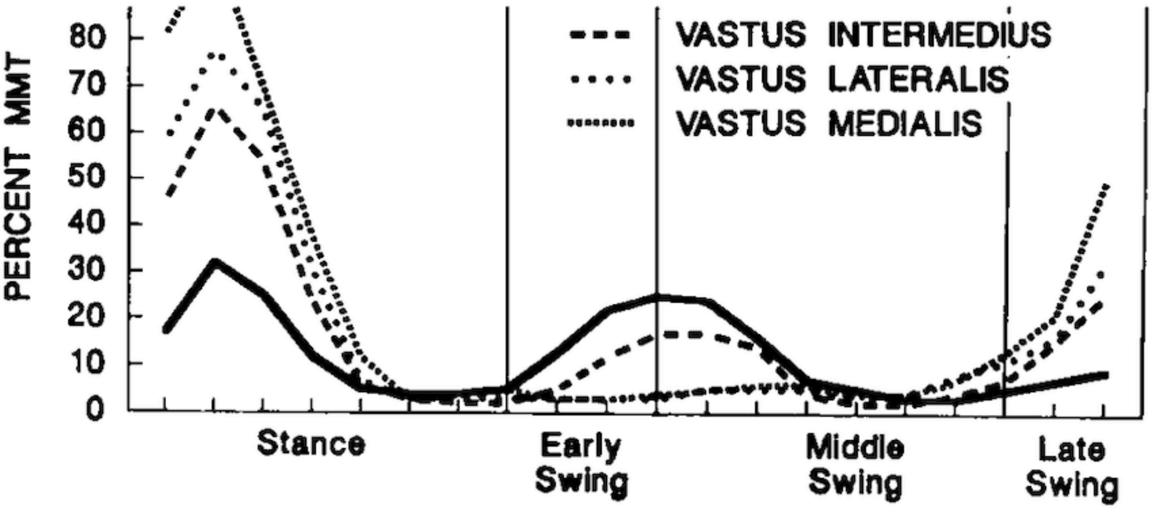


Figure 2. 10: *Quadriceps contraction during the running gait cycle at 4.14m.s^{-1} expressed in relation to a percentage of manual muscle testing (MMT)*
(Montgomery et al., 1994).
You will see the quadriceps active particularly during stance and early-mid swing where co contraction occurs with the hamstrings.

It has been suggested that a functional ratio below 1.00 may be representative of an inability of the hamstrings to tolerate eccentric lengthening while running but also in kicking and jumping as performed in Gaelic football (Aagaard et al., 1998). It would be expected that functional ratios would be higher than conventional ratios as its widely accepted that eccentric force exceeds concentric force and this has been postulated to range between 15-33% (Singh and Karpovich, 1967). Furthermore, eccentric force typically remains constant with an increase in testing velocity whereas concentric force decreases. A systematic review of the literature reveals various ratios at various testing speeds (Table 2.4).

Table 2. 4: *Speed of testing and Functional Ratio (Average +/- SD)*
(Baroni et al., 2020).
As you can see ratios increased, due to concentric force decreasing alongside an increase in angular joint velocity.

Speed (°/s)	fH/Q
30/30	0.59 +/- 0.10
60/60	0.79 +/- 0.19
120/120	1.27 +/- 4.2
180/180	0.96 +/- 0.19
240/240	1.09 +/- 2.2
300/300	1.23 +/- 1.8

At fH_{60}/Q_{60} these ratios can be reduced in injured athletes in comparison to the un-injured athlete (Yeung et al., 2014). While in professional soccer un-injured players (0.8+/-0.15) versus injured (0.65+/-0.21) players differ significantly (Dauty et al., 2003). Based on the current research above, a ratio of <0.8 is plausible to prevent injury at speeds less than 60^0/s while ratios above 1.00 may be required at higher speeds but more evidence is required.

2.4.4 Mixed Ratio

The mixed ratio is a derivative of fH:Q but examines the hamstrings to contract at a eccentrically slower speed while the quadriceps is examined at a faster concentric contraction, in order to evaluate muscle function at similar forces. As in the functional ratio, mixed ratios are useful as they also take into consideration the force velocity relationship between eccentric and concentric muscle contraction with increasing speeds of testing. The relationship in which the quadriceps produce the largest force in conventional ratios and functional ratios below 60 ^{0}/s is reversed in mixed ratios, where the hamstrings is the greatest producer of torque at lower eccentric testing speeds. Consequently, ratios of 1.00+ are expected (Table 2.5). It is a significant ratio for identifying previous muscle injury (Dauty et al., 2003, Croisier and Crielaard, 2000).

Table 2. 5: *Mixed Ratios*

(Baroni et al., 2020).

You will observe an increase in ratios 1 and 3 as there is a greater capacity in this ratio to generate greater hamstring eccentric joint torques at 30^0/s and 60^0/s, whereas the ratio in number 2 decreases to a greater capacity in the quadriceps to generate more concentric torque at 180^0/s and lower concentric torque 240^0/s.

Speed (°/s)	Ratio
1. fH_{ecc30}/Q_{con240}	1.32 +/- 0.26
2. fH_{ecc60}/ Q_{con180}	1.29 +/- 0.20
3. fH_{ecc60}/ Q_{con240}	1.53 +/- 0.30

It is less well reported than its previous counterparts however $fH_{ecc30}:Q_{con240}$ is the strength ratio which showed players most susceptible to HSI and is useful for the prediction of hamstring injury with a cut-off value of 0.8 (Croisier et al., 2008). Also $fH_{ecc30}:Q_{con240}$ has a sensitivity of 2.5%, specificity of 99% and prediction probability of 40.1% (Dauty et al., 2016). While large effect sizes have also been reported (-0.088; 95% CI -1.27- 0.48; I2 0%)

(Maniar et al., 2016). In professional soccer players significant differences with moderate effect sizes for mixed ratios at fH_{ecc30}:Q_{con60} have been reported (Lee and Kim, 2017). The fH_{ecc30}:Q_{con240} is more predictive than H_{180}/Q_{180} ratio and the bilateral H_{60}/H_{60} ratio, the link between the three ratios is beneficial to identify HSI presenting during the season with the likelihood of a hamstring strain injury almost 80%, when the player shows a fH_{ecc30}:Q_{con240} <0.8, a H_{180}/Q_{180} ratio <0.47 and $H_{opp60}/H_{opp60\ ratio}$ less than 0.85 (Dauty et al., 2016).

2.4.5 Other Isokinetic Ratios to Consider

Two other considerations associated with HSI are rate of force development, dynamic control ratio and specific angles of peak torque. The rate of torque development was first considered by Sole et al. (2011) and is calculated as the time taken in millisecs (ms) to reach maximum peak force. It is proposed that this relates to neuromuscular function and sensory motor loops from peripheral to central neural networks (Wallwork et al., 2015). Motor function and, in particular, rate of force development is reduced following injury (Opar et al., 2013c). More recently force platforms have been developed and utilised to investigate neuromuscular performance prior to training and following injury. This has specific application to the terminal swing phase in which the hamstrings are required to develop force rapidly in the transition from late swing to early stance.

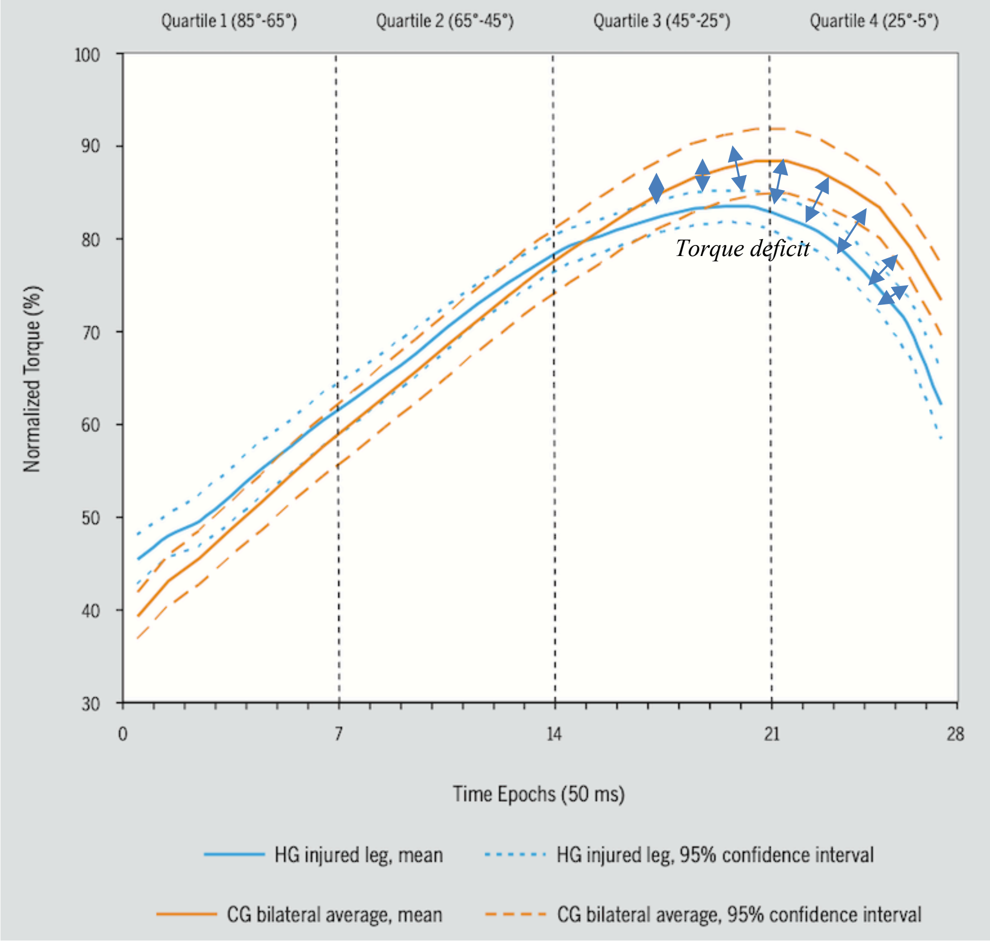


Figure 2. 11: *Normalised BW eccentric peak hamstring torque of injured leg and non-injured group (Sole et al., 2011).*

In Figure 2.11, time to peak torque is significantly lower in injured players and has been related to changes in sarcomeres, fatty infiltration and changes in muscle volume following injury (van Dyk et al., 2018, Aagaard, 2003, Aagaard et al., 2002, Sole et al., 2011). A 13% deficit in muscle activity during eccentric activity, 22% difference in the rate of torque development (Opar et al., 2013c) and a decline in the rate of torque development from 30 Nm/s to 100 Nm/s, have been specifically observed in the bicep femoris and medial hamstrings, all a consequence of HSI (Aagaard, 2003, Wilson et al., 1995).

Angle specific moments are widely used and have been developed for various speeds and angles and it is suggested that these should be used to determine knee joint stability (Aagaard et al., 1998). There is only one study pertaining to HSI in Gaelic football in which the eccentric angle of peak torque occurs at significantly shorter muscle lengths than previously injured players (Figure 2.18) (Mackey et al., 2011). Shorter muscle length angles of PT results in the muscle been worked on the descending limb of the muscle length tension curve, more susceptible to HSI as a result (Brockett et al., 2004, Brockett et al., 2001). Angles of peak torque have been shown to change following eccentric training and this shift towards a longer optimum length is associated with a decreased risk in HSI (Figure 2.12) (Brockett et al., 2004, Brughelli and Cronin, 2008).

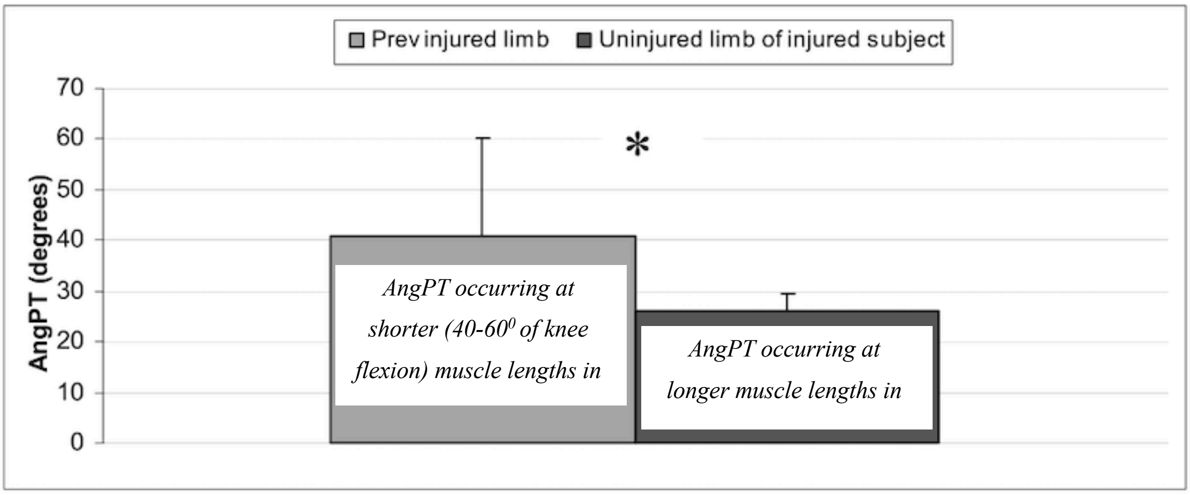


Figure 2. 12: *Mean + SD hamstring Angle of Peak Torque (AngPT) of the injured v uninjured limb at the eccentric angular velocity of 30^0/s ($p<0.05$)*
(Mackey et al., 2011).

The dynamic control profile has also been developed as an option to conventional ratios and represents the eccentric braking effect of the hamstrings relative to the concentrically contracting quadriceps and identifies the range at which concentric quadriceps torque is greater than eccentric hamstrings torque (Figure 2.13) (Graham-Smith et al., 2013). It is postulated that the closer the range angle to 90^0 the greater the range at which the hamstring can tolerate the torque generated by the quadriceps and thereby protect the hamstring from HSI. More recently a study by Alt et al. (2020) investigated and compared the dynamic control profile and the dynamic control ratio and concluded that they correlated weakly and the profile ratio should be favoured, while they also suggested the combination of muscle fascicle length to further investigate its relationship to HSI.

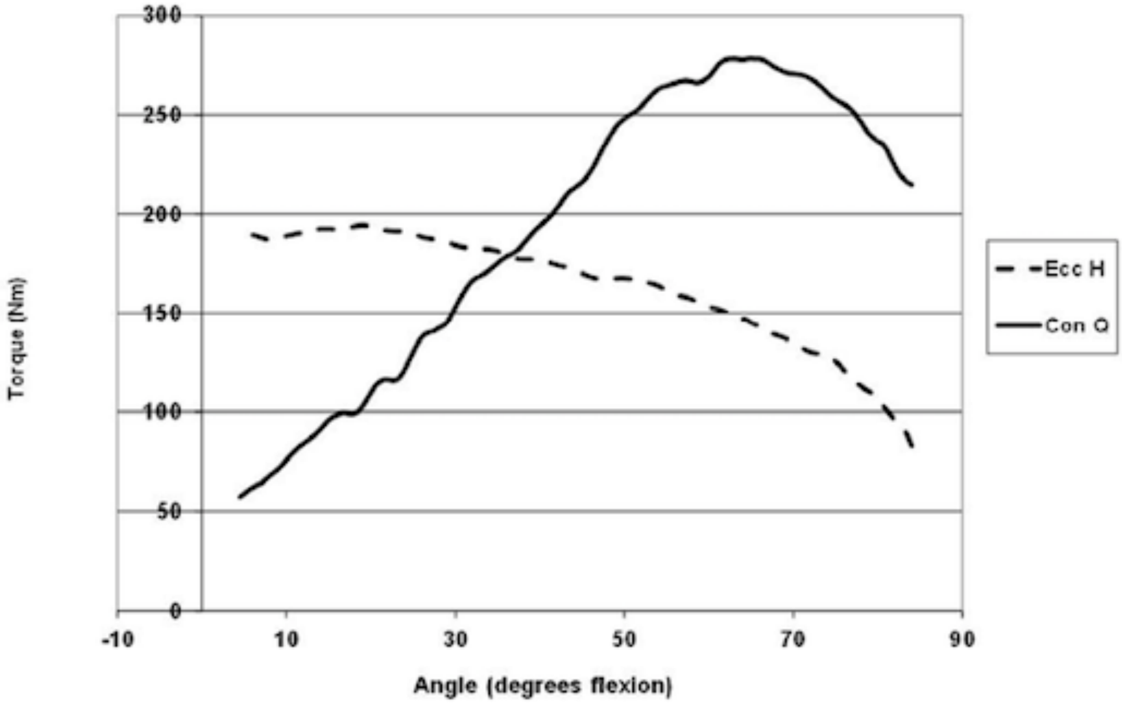


Figure 2. 13: *Angle of crossover*

(Graham-Smith et al., 2013).

You will notice the angle of crossover, the greater the level of eccentric hamstring strength relative to concentric strength the greater this angle becomes.

2.4.6 IKD Methodology in relation to HSI risk

Isokinetic data and its relationship to HSI risk can be somewhat controversial due to the inconsistencies of studies and the lack of corroboration within the literature (Bennell et al., 1998, van Dyk et al., 2016, Zvijac et al., 2013). For example Aagaard et al. (1995) reported a conventional ratio at 60^0/s of 0.45, whereas (Aquino et al., 2007) reported a conventional ratio of 0.80 at the same speed. As in Table 2.6 variations in populations and cohorts (Australian, South American, European, Asian, South American, North American), football codes (Australian rules, AFL, Soccer, Gaelic football), Age (20-29yrs) produce large inter study variations and therefore comparison between cohorts should be undertaken with care. Furthermore, methodological and experimental differences in studies ranging from 18-1252 subjects with injured groups between 6-167, the machine (Cybex, Biodex, Kin-Com, Contrex), practice trials (0-4), joint range of motion (70-110°), joint angular velocities (30-

300°/sec), repetitions (3-10reps), warm-up (nothing-10mins), stretching, alignment of the centre of rotation of the apparatus to the actual joint line, analysis (means, t-test, injured un-injured, dominant v non-dominant, spearmans, logistic regressions, logit, ROC, AUC) and the number of testers (1-5) all differ within the literature and this explains a large portion of the lack of agreement between studies. It also clearly highlights the requirement for a standardised and regulated testing methodology. There is less information regarding these studies in Gaelic football and it is an area that is not well researched (Table 2.7).

IKD isolates muscle testing in a fixed joint position in a single joint movement whereas multi- joint movements are involved in day to day sport. Another challenge is testing at low-moderate joint angular velocities as they are not close to the physiological speeds of high level running which can range between 860-1720°/s (Nagahara et al., 2014, Nunome et al., 2002). Therefore, it is important to recognise that fact that some, Jönhagen et al. (1994) have recommended slower test speeds whilst other researchers have recommended joint velocities of 180°/s (Knapik et al., 1991). Slower speeds may be more accurate in showing ratio deficits even though they do not represent the speeds of sprinting (Orchard et al., 1997). At higher speeds when testing in isokinetic mode, it is particularly difficult to attain a true maximum eccentric contraction throughout joint range of motion where the ability to truly elicit a maximum contraction in the inner and outer range (when the dynamometer lever is nearing full flexion and full extension) becomes reduced. This is compounded by the fact that at times angular velocity does not achieve maximum velocity at speeds over 300^0/s and that when accelerating and decelerating there is a limited window to attaining a maximum contraction at the high speed of testing (Figure 2.14).

Table 2. 6: *Summary of isokinetic dynamometer studies and their methodologies*

You will notice a large range of populations, cohorts, equipment and methodologies.

Authors	Population	Cohort	Machine	Methodology
(Orchard et al., 1997)	Senior professional Australian football team. 22+/-4.1yrs	n=41 Injured n=6	Cybex, Concentric 4 Practice trials + 60^0/s (x3), 180^0/s (x3), 300^0/s (x3)	
(Bennell et al., 1998)	6 Professional Australian football teams and 4 Amateur teams 22.2+/-3.6yrs	n=102 Injured n=12	Kin-Com, Con+Ecc 60^0/s (5-6), 180^0/s (5-6), Range 5-95^0	10 min bike Stretching Dyna head –central
(Dauty et al., 2003)	Professional soccer players Injured 23.2+/-3.1yrs Un-Injured 23+/-3.8yrs	n=28 Injured n=7	Cybex, Con+Ecc Practise (x5), 60^0/s (x2) Range 100^0.	Warm up 100 watts at 70 RPM. Stretching. Dyna head-central
(Brockett et al., 2004)	Australian Rules and track and field athletes.	n=18 Injured n=9	Biodex III, Range 110^0 60^0/s (x7).	
(Croisier et al., 2008)	Belgian, Brazilian and French professional soccer teams 26+/-6yrs	n=482 Injured n=35	Cybex & Biodex III, Range 100^0, Practise 120^0/s (x3) Con; 60^0/s (x3), 240^o/s (x5). Ecc 30^o/s (x3), 120^o/s (x4).	Warmup 75-100 Watts. Stretching
(Fousekis et al., 2011)	4 Professional soccer teams 24+/-4yrs	n=83 Injured n=16	Biodex III, Con 60^0/s, 180^0/s, 300^0/s Ecc 60^o/s ,180^0/s	Warm up 1-15 mins. Stretching
(Zvijac et al., 2013)	32 NFL teams 2.3+/-0.8 yrs	n=1252 Injured n=164	Cybex, Concentric 60^0/s (x3), 300^o/s (x15)	Various
(Dauty et al., 2016)	French Professional soccer players. Injured 25.2+/-4.2yrs Un-Injured 22.5+/-4.8yrs	n=136 Injured n=57	Cybex, Practise 3 at 60^0/s Con 60^0/s (x3), 120^0/s (x3), 180^0/s (x5), 240^0/s (x5). Ecc 60^0/s (x5), 30^o/s (x5), 120^0/s (x5). Range 100^0.	Warm Up 100 Watts at 70 RPM Dyna Head-Central
(van Dyk et al., 2016)	14 Professional soccer teams 24.7+/-4.7 yrs	n=614 Injured n=167	Biodex III, 3 practice reps Con and Ecc 60^0/s (x5), 300^0/s (x10)	Warm up 5-10mins
(Lee and Kim, 2017)	6 Professional soccer teams 24.2+/-4.4 yrs	n=146 Injured n=41	Biodex III, Practise (x 4) Con 60^0/s (x5), 240^o/s (x5) Ecc 30^0/s (x5)	Warm up 10 mins

Table 2. 7: *Summary of isokinetic studies and methodologies in Gaelic football*

Not a well-researched area in GF.

Authors	Population	Cohort	Machine	Methodology
(O'Sullivan et al., 2008)	College Gaelic footballers 21+/-1.8 yrs	n=29 Injured n=15	Contrex, 4 Practice trials Concentric 60^0/s (x3),180^0/s (x3),300^0/s (x3)	Warm up 10 mins Stretching Dynahead central
(O'Sullivan and Burns, 2009)	Female College Gaelic footballers Injured 20.71+/-3.3yrs Uninjured 20.31+/-2.69yrs	n=20 Injured n=7	Biodex III Contrex, 4 Practice trials Concentric 60^0/s (x3),180^0/s (x3),300^0/s (x3)	Warm Up (10mins) Stretching Dynahead central
(Mackey et al., 2011)	Sub elite Gaelic footballers Injured 23.9+/-4.6 yrs Uninjured 20.4+/-1.1 yrs	n=18 Injured n=9	Biodex III Contrex, 4 Practice trials Concentric 60^0/s (x3),180^0/s (x3),300^0/s (x3) Range 20-90^0	Warm Up (5mins) Dynahead central

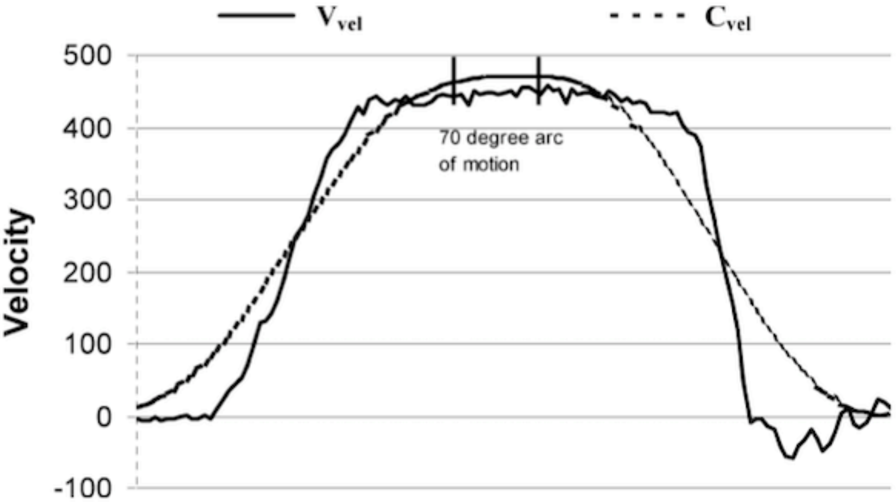
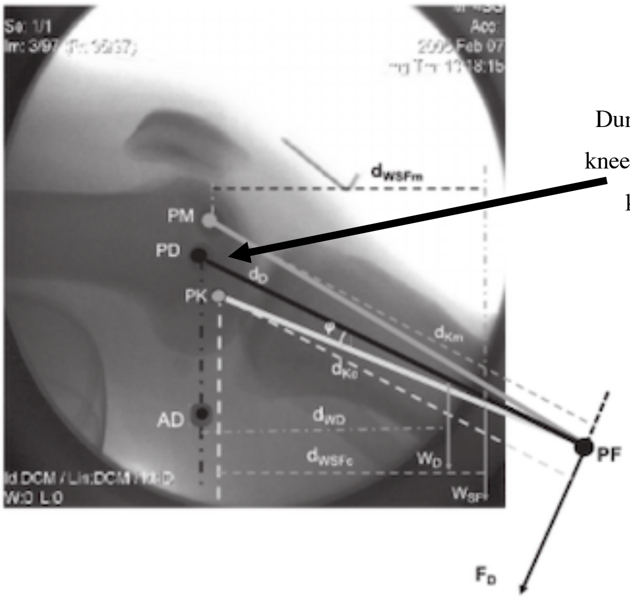


Figure 2. 14: *Angular velocity measures at 500^0/sec with 70 degree arc of motion and criterion measure of velocity (C_{vel}) and raw voltage (V_{vel})*
(Drouin et al., 2004).
You will notice the Cvel does not reach the prescribed 500^0/s and falls short of this by circa 50^0/s.

The majority of the research published to date applies a filter of 10 – 20 Hz and these low pass filters can lead to over-smoothing of the torque curve as peaks on the curve on reduced thereby underestimating particular peaks of torque and the rate of torque development. On the other hand a high pass filter might allow too much noise (Winter, 2009). More recently filtering with a filter cut-off of 150Hz has been recommended (Thompson, 2019). This is to ensure some but minimal filtering to the signal. In relation to the speed of testing, sampling rate has particular relevance, with sampling rates of 100, 200, 500, 1000 and 2000Hz having all been reported (Thompson, 2019). If an insufficient sampling rate is applied at high testing velocities, there may be a potential to underestimate some points on the torque curve. A sampling rate of at least 1000 Hz is proposed by (Thompson, 2019). Torque artefacts are also more prevalent at higher speeds of testing (Taylor et al., 1991) while it is also recommended to use lower testing speeds to minimise the inertial effects associated with high angular velocities (Iossifidou and Baltzopoulos, 2000). Furthermore, in isokinetic mode at high speed, the dynamometer head accelerates and decelerates which leaves even a smaller window to ensure a true maximum eccentric contraction is maintained at a constant speed. Isokinetic mode is initiated by the participant in that a muscle contraction is applied prior to movement of the lever arm. Alternatively, passive mode does not require this initial contraction to begin the movement and maybe worth considering as a smooth eccentric contraction can be applied to the head of the dynamometer both in inner and outer ranges.

It is also important to consider the dynamometer head as the moment is measured directly around its centre of axis and it is important to ensure the axis of rotation (knee) is aligned centrally during both eccentric and concentric contractions of both the hamstrings and quadriceps. Errors reported within the literature with movement and misalignment of the knee joint are reported to range between 10-17% (Arampatzis et al., 2004, Kaufman et al., 1995) but values as high as 19% have also been reported (Tsaopoulos et al., 2011) A 10^0 shift in the axes of rotation relative to its length results in a 10% moment error (Reimann et al., 1997). The majority of isokinetic studies have not corrected or considered minimising these misalignment issues (Figure 2.15).



During isometric knee extension, the knee angle

Figure 2. 15: *The lower leg axis of rotation (Tsaopoulos et al., 2011).*

With potential for measurement errors due to misalignment/movement of the centre of axis performed isometrically at 90^0 and 20^0 degrees of knee flexion where PD: centre of rotation of the dynamometer; PK: centre of rotation of the knee joint; PM: external marker placed on the lateral femoral epicondyle; PF: point of force production.

One solution is to align the centre of the knee joint and the dynamometer head in mid-range under an active submaximal contraction. This is an important solution to minimise these potentially large measurement errors by placing the lever arm in mid-range strapping and aligning the knee during an active isometric contraction of the muscle being tested

(Baltzopoulos et al., 2012). This in turn would require that isolated testing was undertaken for each specific muscle group with no contraction of the antagonist. When calibration, gravity correction, and patient positioning are all standardised further reliability increases (>0.8) are reported (Pincivero et al., 1997, McCleary and Andersen, 1992, Higashihara et al., 2018).

2.4.8 Conclusions and Future Research

There are a large number of methodologies within the literature investigating various IKD ratios in respect of HSI which generally involve Australian rules or Soccer cohorts. There is very little information on Gaelic football and providing some data in respect of the sport would address this discrepancy within the literature.

Methodologies within the literature also differ in respect of warm, repetitions, trials but the main limitation of IKD is measurement error which can account for the large variability and lack of consensus for specific ratios. A methodology in which these measurement errors are addressed by :

1. addressing the alignment of the dynamometer head through active alignment under contraction
2. utilising a speed of testing providing reliable data
3. utilising passive mode of measurement for eccentric assessment

This would ensure that these measurement errors are minimised. Furthermore investigation of the strength and peak torque of the knee flexors and extensors (concentric and eccentric) at 60^0/sec and 180^0/sec, including the IKD ratios as discussed previously, will further add to the literature in terms of investigating the association of IKD and HSI in Gaelic football.

2.5 Nordbord

The Nordbord testing system™ was developed from the Nordic hamstring style strength assessment. Hamstring strength or force is assessed and reported via two loads cells while performing an NB_{Ecc} fallout and has a moderate to high retest reliability of (ICC=0.83-0.90) (Opar et al., 2013a). The test is performed by kneeling on a pad, ankles placed into the instrumented (load cells) restraints of the Nordbord device, with the lateral malleolus immediately superior to the restraints (Figure 2.16). Participants then lean forward as slow as possible, resisting the falling movement with both limbs by pulling into ankle hooks, hands across their chest maintaining trunk and hips in a neutral position through the entire movement. The force data is then transferred to a tablet device (iPad, Apple Inc.).

Figure 2. 16: *Nordic Fallout*

You will see load cells attached at the ankle, start position is with trunk vertical and finish position is with trunk horizontal.

As in Table 2.8 it has been widely reported in the literature for a number of sports and these values range between 309-486N and 3.65-4.3N.Kg^{-1} with maximum values reported for male elite alpine skiers of 548N. Values for elite alpine skiers are somewhat higher when comparing these to the various football codes and may reflect the stress and strain of downhill skiing where skiers are required to attain speeds over 100 miles per hour, tolerate large kinetic forces (force/friction acting between the surfaces) and ground reaction forces (re-active ground force) up to 2000N (Gilgien et al., 2013).

Table 2. 8: *Eccentric strength (Nordbord) in various sporting populations*
[a1](Roe et al., 2020); [a2](Roe et al., 2018a); [b](Timmins et al., 2015); [c](Buchheit et al., 2016); [d](Opar et al., 2015); [e](Bourne et al., 2015).
Gaelic footballers produce more force than Australian rules footballers and rugby players in respect of body weight.

Sport	Time of season	n	N	N.kg^{-1}
Gaelic Footballers				
Elite	Pre-season[a1]	161	365(351-378)	
Elite	In-season[a1]	24	350(315-385)	
Elite	In-season[a2]	148	361(348-376)	4.3(4.1-4.5)
Soccer Players				
Elite	In-season[b]	131	309.5 +/- 73.4	4.11+/-0.9
Elite	In-season[c]	14	411+/-65	
Elite	In-season[c]	41	371+/-77	
Sub elite	In-season[c]	16	336+/-55	
Australian Rules				
	Pre-season[d]	157	330+/-73	4.18+/-0.92
	In-season[d]	153	323+/-80	4.09+/-1.01
Rugby players				
Elite	In-season[e]	75	366.9+/-76.9	3.65+/-0.71
Sub elite	In-season[e]	65	387.9+/-96.3	4.00+/-0.93
Alpine Skiers				
Females	In-season[f]	19	340+/-48	
Males	In-season[f]	12	486+/-62	

In absolute terms, Gaelic footballers, soccer players and rugby players have very similar hamstring strength. Scores in Australian rules footballers are approximately 15% weaker, while rugby players are weaker than their field playing counterparts in terms of relative hamstring strength (Table 2.8). Rugby players tend to be 10kg heavier on average, than both Australian footballers (87.3+/-8.2kgs) and Gaelic footballers (86.4+/-6.2kgs). The difference in absolute and relative scores can be explained by the fact that a linear positive relationship exists between body weight and hamstring force ($p<0.01$) (Figure 2.17) (Ruan et al., 2021). The similarity of relative values between Gaelic footballers and Australian rules players maybe reflective of training and match demands as Australian rules players are reported to cover >653m at ≥24km h^{-1} weekly (Ruddy et al., 2018) while Gaelic footballers cover 8889m, with 18% of this at high speed pace >17km/h (Malone et al., 2016).

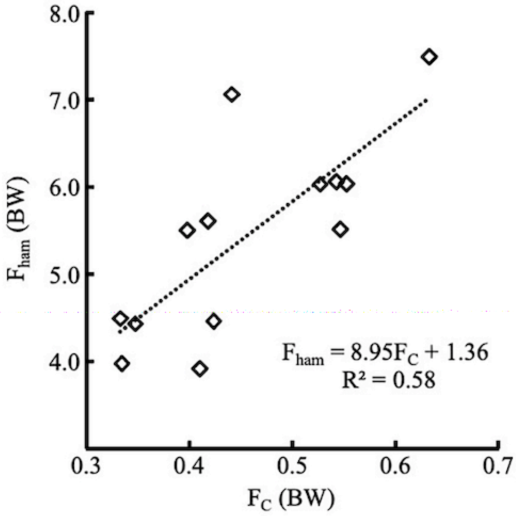


Figure 2. 17: *Linear relationship between body weight and hamstring force (Ruan et al., 2021).*

F_c is the contact force at the ankle hook measured by the Nordbord; F_{ham} is estimated hamstring force a significant but not very high correlation between hamstring force and contact force at the ankle indicating that the contact force at the ankle is not equal or linear to hamstring force.

In terms of prospective injury, the use of the device is widely debated particularly in respect of a cut off point for HSI prevention. Australian rules footballers with hamstring strength levels below 256N at the start of the season were 2.7 times more likely to sustain a hamstring injury (Opar et al., 2015). Elite level soccer players are also reported to be more susceptible to future HSI with strength levels below 337N associated with 4.4 times the risk of future injury (Timmins et al., 2016a). Two other studies (van Dyk et al., 2017, Roe et al., 2020) have more recently attempted to apply cut off points both for a large soccer (n=413) and Gaelic football cohort (n=185) and both do not support these cut off points for future risk of injury. Most recently a meta-analysis revealed no significant differences in respect of absolute and relative scores and Nordic hamstring exercise provides limited pre-season screening value (Opar et al., 2021) and identification of specific thresholds in GF are required with respect to HSI.

Strength asymmetries and imbalances have also been investigated. During pre-season 20% of elite rugby union players with a maximum strength imbalance ≥15% experienced an in-season hamstring injury and players with this characteristic were 2.4 times more at risk, with ≥20% asymmetries 3.4 times at greater risk of injury (Bourne et al., 2015). It is widely accepted that between limb imbalances in eccentric strength increase the occurrence of hamstring strain injury (Orchard et al., 1997, Jönhagen et al., 1994, Croisier et al., 2008, Fousekis et al., 2011, Bourne et al., 2015). Neuromuscular fatigue during sport alters the running cycle by creating stride to stride variations which in turn may predispose/overload a weaker hamstring predisposing to a higher risk of injury (Chumanov et al., 2007). However no statistically significant maximum force differences were found between injured (354 N, 95% CI 326-382) and uninjured limbs (364 N, 95% CI 355-374), nor for average force between injured (330 N, 95% CI 300- 357) and uninjured limbs (336 N, 95% CI 327-347) (Roe et al., 2020) in a cohort of Gaelic footballers. This has also been previously corroborated by van Dyk et al. (2017) in a group of elite soccer players. Interestingly there seems to be no pattern in relation to HSI occurrence and strength in the nordic hamstring exercise (NHE) as 7.0% of limbs that generated greater maximum force (+6%) sustained a HSI while 8.8% of weaker limbs (-7.9%) became injured. In relation to between-limb imbalances, it was found that only the ratios based on the peak force averaged across 6 trials had acceptable reliability values (ICC = 0.85; 95% CI 0.71–0.93; SEM = 5%, 95% CI 4–6%) (Opar et al., 2013c). The majority of studies to date utilise peak, rather than average forces. The importance of hamstring strength in long lever positions has previously been discussed and an important consideration is the break point angle (the point at which eccentric contraction cannot be maintained) in which it has reported to occur in high performers at 126±6° and low performers at 103±7° (Ripley et al., 2020). It has also been reported in another study that no participants completed testing through full range (Sconce et al., 2015). Furthermore a poor correlation has been found between peak isokinetic hamstring eccentric torque (60°/s) and forces measured with the Nordbord device ($r = 0.35$; $r^2 = 12\%$) (van Dyk et al., 2018) and it was suggested that this is due to the device assessing eccentric strength in shorter ranges whereas isokinetic assessments allow maximal contraction throughout and into outer range limits. Some authors also perform the NHE at 10^0/s (Lee and Kim, 2017) which may also explain this difference within the literature. Furthermore resisting eccentric contraction during the exercise requires some technical proficiency and very often testing is undertaken without prior practise or knowledge of how to complete the movement.

More recently the validity of the measurement has been queried as a significant but not very high corelation between peak hamstring force and peak contact force at the hook has been determined, with contact force at the hook only accounting for 58% of hamstring eccentric force (Ruan et al., 2021). Furthermore, the hamstring forces exhibited during testing, 5.5 times body weight are also a lot lower than those in running (Ruan et al., 2021). When hamstring forces during sprinting are 45-64% greater, at 8-9 times bodyweight (Sun et al., 2015, Schache et al., 2012).

Nordbord data is reported in force (N) rather than torque (Nm) which does not take into account the length of the lever in generating the force. Consequently, it is not possible to compare groups of players with different body mass distributions, particularly with regards to the upper body. Particularly as height and weight influence the load applied to the knee joint during the Nordic hamstring exercise (Opar et al., 2013a) and body mass influences maximum eccentric knee flexor strength as existing research reports an increase of 4N in maximum eccentric knee flexor strength per 1kg increase in body mass (Buchheit et al., 2016). To report torque data normalised for body weight for different football codes would allow comparison between codes and account for the different populations of various anthropometric characteristics. This moment arm has been recently researched where the length of the shank has been taken into account to measure moment of the hamstring (Figure 2.18). Furthermore, we know anthropometric differences exist between the reported cohorts throughout the literature, with Australian footballers (188.0+/-7.2cm) one of the tallest cohorts in which they are on average 5cms taller than their Gaelic football counterparts and where rugby players are on average 10kgs heavier.

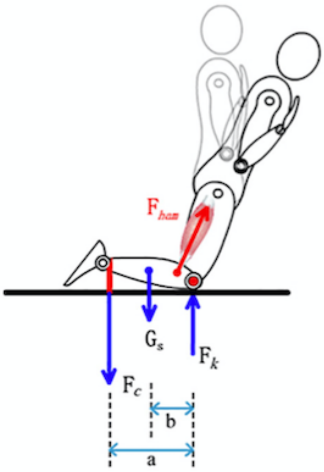


Figure 2. 18: *Moment arm for hamstring force during the Nordic hamstring exercise (Ruan et al., 2021).*

Where Fham is estimated force of the hamstrings, Fc contact force at the ankle, G_S *gravity force of the shank,* F_k *force at the knee, a=distance between knee and ankle, b= distance between knee and centre of gravity force.*

2.5.1. Conclusions and Future Research

There is a some debate as to the specific cut off points and NB_{ECC} strength and its association with HSI. Investigating the Nordbord and comparing it to other devices in which eccentric or isometric strength is measured would help resolve this debate. Reporting data in torque rather than newton's would be of benefit when comparing between various sports and cohorts and create sport specific thresholds.

2.6 Isometric Strength and HSI

Isometric testing in which force is developed in a static position, is inexpensive, easy and relatively quick to administer for large populations and has a low risk of inducing muscle soreness in comparison to eccentric contractions (Opar et al., 2013a). Maximum voluntary isometric contraction (MVIC) has been used to measure hamstring muscle function and strength in various positions. It has been proposed that a quasi-isometric phase exists following eccentric contraction in the transition during the swing phase to early stance (Van Hooren and Bosch, 2017). This argument is an application of previous research in relation to the gastrocnemius. A quasi-isometric (holding a isometric contraction until activation/de-activation causes shortening or lengthening) function exists in the gastrocnemius and soleus fascicles of animals during the late swing phase indicating that quasi-isometric contraction may exist following eccentric contraction in the transition from swing to early stance phase of human running (Roberts et al., 1997, Gabaldon, 2004, Gillis and Biewener, 2001).

There have been a number of methods used to measure MVIC these include sphygmomanometers (Schache et al., 2011b, Herzog and Read, 1993), hand held dynamometers (Kelln et al., 2008), externally fixed load cells (Charlton et al., 2018a, Wollin et al., 2016), isokinetic dynamometry (IKD) (Krustrup et al., 2011) and more recently force plates (FP) (Figure 2.19) (O'Keefe, 2020). These systems have attempted to measure the force output of the hamstrings at various lengths by manipulating knee flexion 20-90^{o}, with various degrees of hip flexion and either in a prone supine or in the case of IKD in a seated position. Handheld dynamometers have been used to assess return to play following injury. It has good reliability (0.73-0.83) and is usually assessed in a prone position with knee flexion angles of 15^{0} and 90^{0} and the current research indicates that there is very little prognostic value in isometric strength and HSI for return to play (Reurink et al., 2016).

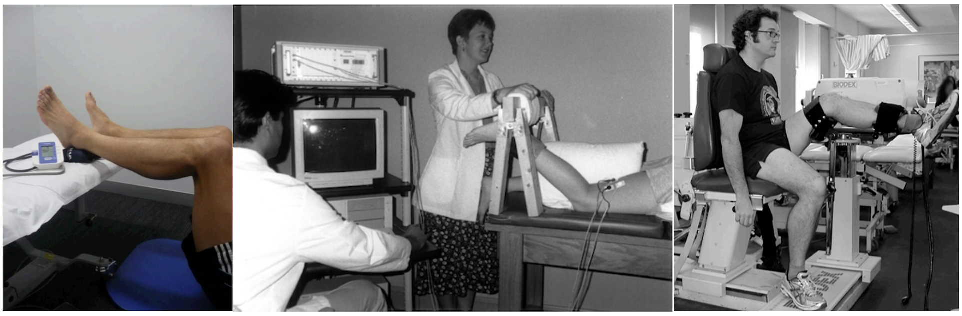


Figure 2. 19: *Measurement of MVIC using various devices.*
Where left side is isometric assessment (prone) of the knee flexors at 90^{0} of knee flexion using a sphygmomanometer, using a load cell in 150^{0} of knee flexion, right sided is IKD assessment (seated) in hip flexion at 150^{0} degrees of knee extension.

Maximal isometric knee flexion peak force, torque and normalised torque measures are significantly reduced in semi-professional Australian rules footballers with a previous history of HSI and evident up to three seasons, compared to athletes without previous HSI (Charlton et al., 2018b). However, their method of testing was unclear, as they cite a method using an externally fixed dynamometer in which strength was measured according to a previous paper with a 5% standard error of measurement (SEM). Unfortunately, there is no reference to this within that paper in which they investigate clinical markers in relation to HSI in guiding return to play. Charlton et al. do cite that for every unit decrease in knee flexion torque normalised to body mass, the chance of an athlete having a previous history of HSI increases by 82%. A previous case study by Schache et al. (2011a) on an athlete which became injured using a digital sphygmomanometer at 90^0 knee flexion, suggested that, MVIC was reduced by 10.9% 5 days prior to HSI, however to date this has been un-corroborated. External load cells and force plates have been modified to measure MVIC in relation to post match fatigue (Figure 2.20 and 2.21). This has been measured via two external load cells in a prone position, 45^0 of hip flexion and knee flexion at 30^0 and demonstrated good inter and intra-tester reliability (0.87 95% CI = 0.75–0.93) and reliability (0.86 95% CI, 0.74–0.93), SEM% 5.0 and MDC% 14.0 (Wollin et al., 2016). They used two practice repetitions and one maximal test effort of each leg for a MVIC of 5 s in duration followed by 10 s rest between practices and 20 s rest between sets. Following on from this they preceded to monitor in-season hamstring recovery characteristics via MVIC in male international soccer players and report hamstring strength to recover 48 hours post games (Wollin et al., 2016).

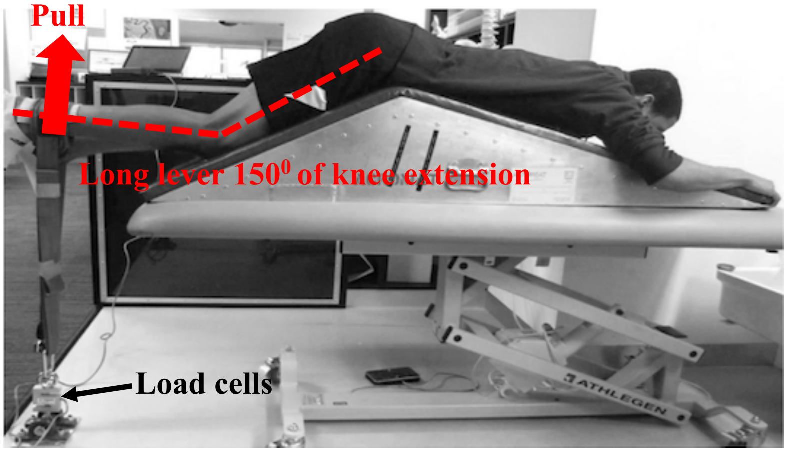


Figure 2. 20: *External load cells and MVIC (Wollin et al., 2016).*

Force plates have also been adapted to measure MVIC at both 90^0 and 30^0 of knee flexion in a supine position by pushing the heel into the platform for 3 secs, repeated 3 times with 2 mins of rest between each set and the highest peak force recorded (Figure 2.26). It was then used to determine muscle recovery post game and showed high reliability at 90° (CV = 4.3%, ICC = 0.95, ES = 0.15) and 30° (CV = 6.3%, ICC = 0.86, ES = 0.05) with good sensitivity to determine the magnitude of match-induced fatigue of the posterior lower limb muscles and the potential to track recovery (McCall et al., 2015a).

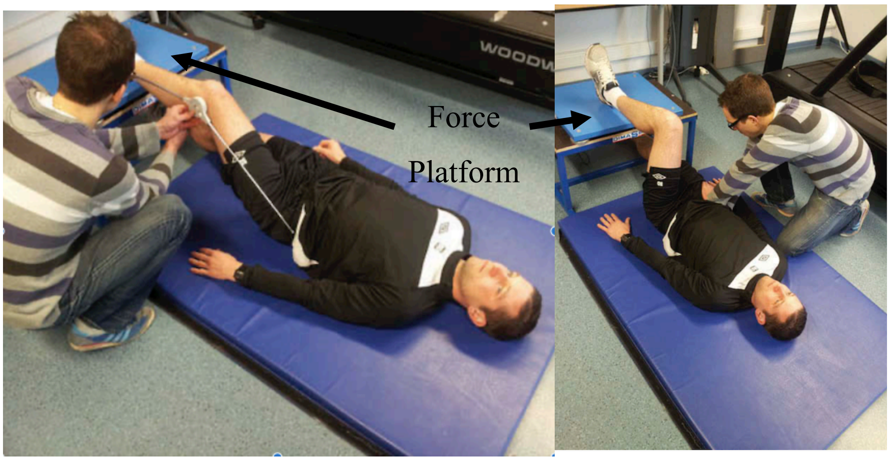


Figure 2. 21: *MVIC using force platform*
(McCall et al., 2015a).
Left side is long lever assessment at 150^0 *of knee extension, right side is short lever assessment at* 90^0 *of knee flexion.*

This method has been adapted further in a 90:20 (90^0 hip flexion: 20^0 knee flexion) isometric posterior chain strength test (Matinlauri et al., 2019). Again this has been used mainly for the measurement of post-match fatigue in a English primer league U21 team. Hamstring strength significantly decreased from baseline at +24 hours and +48 hours ($p \leq 0.05$) in both limbs while a significant negative correlation ($p \leq 0.05$) was observed between sprint distance and changes in dominant limb hamstring strength indicating that increases in sprint running loads could further reduce hamstring strength and prolong recovery (O'Keefe, 2020). This has obvious implications for HSI risk towards the end of games due to muscle fatigue and this is thought to be associated with the decline in muscle glycogen for up to 48 hours post exercise (Bangsbo et al., 2006) and the intramuscular damage associated with exercise of high intensity or eccentric contractions (Ispirlidis et al., 2008, Nédélec et al., 2012). In comparison to the isolated IKD protocols this test requires contraction about the knee and hip and more similar to that seen in running where the gluteal is active during hip extension.

MVIC of the hamstrings has also been measured seated using IKD at 80°, 60°, 40°, and 20° of knee flexion with various degrees of hip flexion, 0-90° (Herzog and Read, 1993, Warren, 2008, Warren et al., 2010, Charlton et al., 2017). It has been recommended to test in a supine position with the hips and knee flexed to 90° to isolate hamstring contraction and produce the greatest arm moment (Herzog and Read, 1993). Isometric contraction should be held against resistance for at least 6 s to allow for peak muscle tension (Kisner and Colby, 1985) while a 10s-1min rest period after an isometric contraction is cited as an appropriate rest interval (Fiebert et al., 1998). More recently McCall et al. (2015a) used 3 second isometric contractions and repeated this three times with a 2 min rest interval between each repetition which assessing MVIC on a force plate.

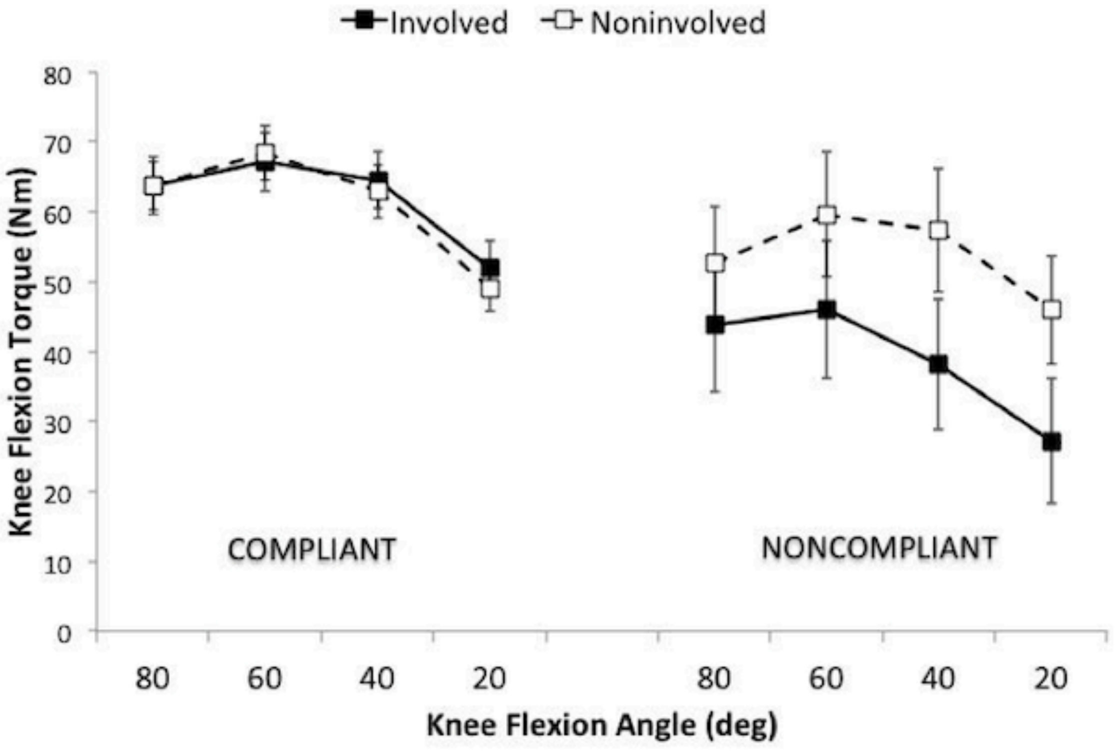


Figure 2. 22: Length tension relationship in involved V non-involved participants of compliant and non-compliant athletes (Tyler et al., 2017).

I*n seated IKD assessment of MVIC you will notice a weakness in the involved side for the non-compliant athletes.*

More recently this has been used to evaluate compliance levels (Figure 2.22) in recovering from acute HSI by investigating isometric knee-flexion-strength deficits at short (80°) to long (20°) muscle lengths for compliant and noncompliant athletes. Investigating short to longer muscle lengths allows assessment of the length tension relationship and detecting potential deficits at longer muscle lengths may be important as this is the portion in late swing/early stance in which HSI occurs. Significant strength deficits were apparent in noncompliant athletes but not in compliant athletes indicating the importance of rehabilitation for recovery from HSI (Figure 2.23). They also evaluated eccentric strength and performed this from 90° to 20° knee flexion at 20°/s to evaluate the length tension relationship and they argue that isometric testing is preferable to isokinetic testing for ensuring accurate correction of joint torques for the effects of limb mass and passive muscle tension.

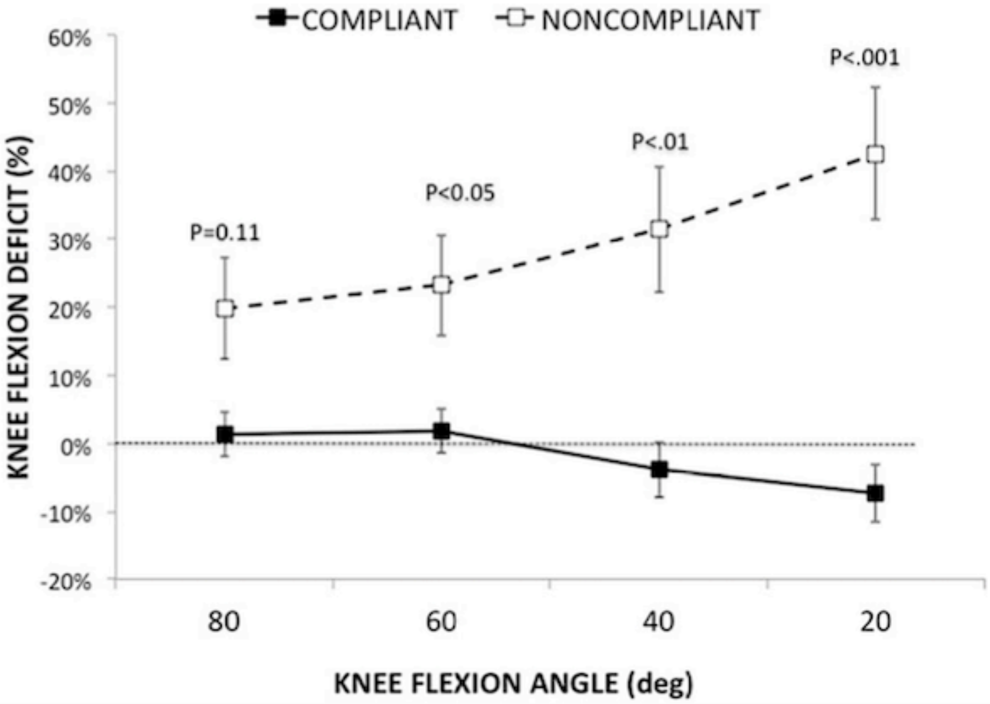


Figure 2. 23: *MVIC strength deficits in compliant v non-compliant participants with HSI (Tyler et al., 2017).*

You will notice non-compliant athletes have significantly lower levels of MVIC which increases as the lever length increases. This increases the potential for HSI in late swing (for non-complaint athletes) as underlying weakness in this long lever position predisposes to injury.

IKD has also been used to identify the rate of torque development during MVIC of both the quadriceps and the hamstrings and the rate of torque development (RTD H/Q) ratio in 30^0 of knee flexion, RTD H/Q calculated by dividing the knee flexors RTD by the knee extensors RTD into the corresponding time interval (Table 2.9). There were no differences when comparing to players with previous HSI to those without, however professional players showed a trend towards lower RTD H/Q at early contraction and higher H/Q ratios at late intervals which maybe suggestive of a greater protective mechanism for HSI where players are required to maximal contract the hamstrings in explosive movements (50-250ms) (Correia et al., 2020).

Table 2. 9: IKD Rate of Torque Development hamstring to Quadriceps ratio (RTD H/Q) (Correia et al., 2020).

You will notice that previously injured players had significantly lower MVIC RTD for the very initial phase of muscle contraction.

Time (ms)	Uninjured players (n=12)	Previously injured (n=12)
H/Q 50	1.69+/-0.66	1.43 +/- 0.73
H/Q 100	0.94 +/- 0.35	0.93 +/- 0.38
H/Q 150	0.73+/- 0.25	0.83+/- 0.25
H/Q 200	0.72 +/- 0.22	0.85 +/- 0.25
H/Q 250	0.72 +/- 0.24	0.84 +/- 0.26

MVIC has also been used to assess the activity of the medial and lateral hamstring at 45^0 of knee flexion, the lateral hamstrings contribute a significantly greater percent (63.4%) of the total EMG than the medial hamstrings ($p<0.0001$). Interestingly the lateral hamstrings contributed less force in comparison to the medial hamstrings during submaximal contraction which suggest the lateral hamstrings maybe required for the more powerful contractions and help explain the greater incidence of injury in this portion (Fiebert et al., 2001). The BF has also been shown to be maximally activated in outer ranges at 15^0 and 30^0 whereas the semi-membranous are maximally activated at the shorter muscle lengths with knee flexion angles of 90^0 and 105^0 (Onishi et al., 2002).

2.6.1 Conclusions and Future Research

MVIC and its relationship to HSI is poorly researched and more novel approaches are warranted in relation to MVIC measurements in which there is more consideration given to the position of testing, the specificity of late swing and early stance and unilateral v bilateral testing. When tissue disruption does occur, it does require classification and determination of the severity or grading, to assist in the prognosis of recovery or time to return to play. MVIC maybe more advantageous than eccentric assessment as it is safer to administer in the case of the injured athlete and when screening complete squads.

2.7 Classification of muscle Injury

HSI is pain in the posterior thigh with immediate cessation of activity/sport and results in time loss from either training or games (Timmins et al., 2015, Roe et al., 2018b). HSI can be classified according to site of injury (proximal or distal), mechanism of injury (contusion or non-contact), tissue involved (muscle or tendon) and further classified according to the nature of the injury (chronic or acute). Grading systems have been established to indicate the severity of the injury and to provide prognosis for return to play.

Initially this was a clinical based systems (O'Donoghue, 1958) and progressed to the introduction of both ultrasound (Peetrons, 2002) and MRI (Stroller, 2007) to aid in grading the severity of injury, while also providing a more specific intramuscular diagnosis for prognosis and return to play. The Munich classification (Mueller-Wohlfahrt et al., 2013) is one system highly reliant on MRI to aid diagnosis (Table 2.10). Another system which is an evidence based informed system has also been devised describing the mechanism of injury (M), location of injury (L), grading of severity (G), and number of muscle re-injuries (R): MLG-R (Valle et al., 2017). The British athletics muscle injury classification provides a diagnostic framework also via MRI (0cm, 5,cm, 10cm, 15cm), to diagnose the extent (0-4) and site of injury (a; myofascial, b; muscular or c; intra-tendinous) (Pollock et al., 2014). It has been more widely researched in that it demonstrates good intra and inter-rater reliability and has good correlation with prognosis for return to play and return to full training (Patel et al., 2015, Pollock et al., 2016). Even though MRI in the grading of HSI has been advocated (Figure 2.24) (Mueller-Wohlfahrt et al., 2013, Pollock et al., 2014, Valle et al., 2017). There is limited evidence within these new classifications systems for predicting return to play following HSI (Reurink et al., 2015a).

Table 2. 10: *The Munich classification system for Hamstring Injury (Mueller-Wohlfahrt et al., 2013).*

Type	Classification	Definition
1A	Fatigue Induced muscle disorder	Circumscribed longitudinal increase of muscle tone (muscle firmness) due to over exertion, change of playing surface or change in training patterns
1B	Delayed onset of muscle soreness	More generalised muscle pain following unaccustomed deceleration movements
2A	Spine related neuromuscular disorder	Circumscribed longitudinal increase of muscle tone (muscle firmness) due to functional or structural spinal/lumbopelvic disorder
2B	Muscle related neuromuscular disorder	Circumscribed (spindle-shaped) area of increased muscle tone (muscle firmness). May result from dysfunctional neuromuscular control such as reciprocal inhibition
3A	Minor partial tear	Tear with a maximum diameter of less than a fascicle bundle
3B	Moderate partial muscle tear	Tear with a maximum diameter greater than a fascicle bundle
4	(Sub/total) muscle tear/tendinous avulsion	Tear involving subtotal/complete muscle diameter/ tendinous injury involving the bone-tendon junction
Contusion	Direct injury	Direct muscle trauma caused by blunt external force leading to diffuse or circumscribed haematoma causing pain and loss of motion

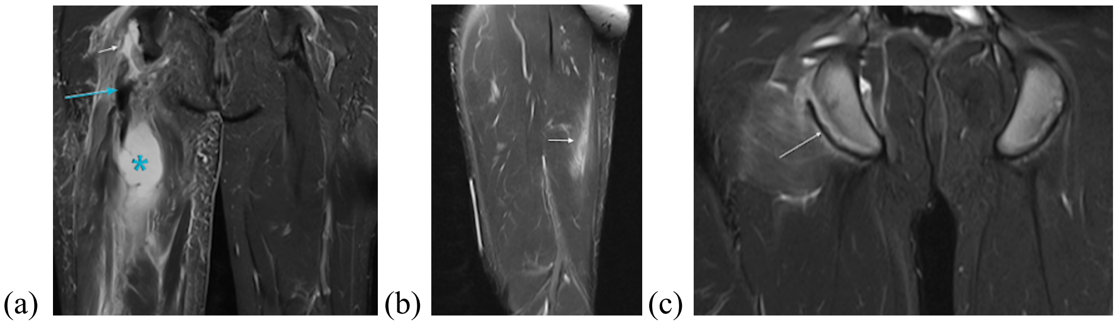


Figure 2. 24: *MRI and HSI*
(Matrovic & Koulouris., 2016).
(a) right hamstring avulsion at the ischial tuberosity (white arrow) (b) strain of the distal MTJ of the long head of biceps femoris (c) ischial fracture (white arrow).

These classification systems also require further corroboration in the form of clinical assessment. This includes location and palpation of the site of injury which has good correlation with MRI and more proximal injuries associated with a longer recovery time (Askling et al., 2007). There is a strong correlation with injury to the subjective visual analogue scale (VAS) of pain in which pain is self-rated pain is with scores ranging from 0 (no pain) to 10 (very severe pain) (Boonstra et al., 2008). This is significantly associated with time to recovery (Guillodo et al., 2014). Range of motion is reduced following hamstring injury and active knee extension (AKE) and passive straight leg raise (PSLR) have been used to assist in the diagnosis and prognosis of hamstring injury with bilateral deficits of $<10^0$, 10-25^0, $>25^0$ associated with Grade I, II and III injuries respectively (Schneider-Kolsky et al., 2006). Initial deficits in PSLR 9 days following injury are 21% and these decline thereafter to 13-6% 10-30 day's post injury (Maniar et al., 2016). Interestingly, for every degree of deficit experienced following injury it was found to increase the risk of re-injury by 13% (De Vos et al., 2014). Strength testing to date has not been correlated with acute HSI as current modes of testing are not safe with acute injury present. It is reasonable to assume strength deficits exist following injury and as in PSLR these could be used to assist in the diagnosis and prognosis of HSI.

2.7.1 Conclusions and Future Research

There is a need for relevant strength tests with discriminative and predictive ability (Heiderscheit et al., 2010). Isometric strength in long lever positions (0-15 degrees) is an independent predictor of re-injury (De Vos et al., 2014) and can be possibly used to support the classification process. To date no objective strength data is available for injury classification, and this would aid the clinician in HSI diagnosis and prognosis and may also contribute to a smooth, effective and safe pathway to return to sport.

2.8 Running and HSI

The majority of HSI I GR occurs during running and it is important to fully understand the mechanism involved. During high speed running the hamstrings undergo extreme length changes and stretch, over extending it, making it vulnerable and responsible for the large incidence of HSI whilst running (60%) (Askling et al., 2008, Brooks et al., 2006). The hamstrings are designed for low force production, high rate contractions and high stretching velocity (Friederich and Brand, 1990). Within the hamstring complex their architecture is different to ensure a broad range of velocity and contractile capabilities to tolerate peak muscle forces at various degrees of knee flexion and hip flexion and extension during the gait cycle. This begins with toe off into early swing (maximum hip extension 195^0), mid swing (peak knee flexion 40^0, peak hip extension of 1195 ^{0}/s) & late swing (peak hip flexion 100^0) and transitions into early stance beginning at foot strike, mid stance (knee flexion to extension) and finally to late stance (knee extension, peak hip extension). These phases of the gait cycle place various stresses and strain on the hamstring musculature with large net peak muscle forces as illustrated in Table 2.11 (80kg player). Up to 5200N eccentric force is placed upon the hamstrings and this is even before external loads such as physical contact are considered or initiated, which create local tissue strain and further pre-dispose to injury.

Table 2. 11: *Peak Muscle Force (N) in Gaelic football*

(adapted from Chumanov et al. (2007).

You will notice large net peak muscle force for the hamstrings.

	BF	SM	ST	Net
80% max speed	1208-1501	1512-1890	512-640	**2880-3600**
Max Speed	1712-2140	2232-2790	632-790	**4160-5200**

Hamstring injuries during high speed running usually affect the BFlh at a mean distance of 6.7cm distal to the ischial tuberosity at the muscle tendon junction (Askling et al., 2007) (Van der Made et al., 2013). Hamstring injuries which involve hip flexion and knee extension are usually located even more proximally at a mean distance of 2.3cm from the ischial tuberosity (Askling et al., 2007). This could be due to the complexity of the anatomy proximally, in which, the hamstrings share a common tendon and the interaction of these muscle tendon units.

It is difficult to correctly identify the specific time of HSI in running, due to the neural delays or latencies in reporting the injury (Kenneally-Dabrowski et al., 2019, Schache et al., 2010). Particularly, as the deceleration during the late swing phase of high-speed running usually occurs in less than 250 milliseconds (Rodríguez-Rosell et al., 2018). As per table 2.12, there is a wide consensus however, that HSI is likely to occur in either late swing phase or early stance (Chumanov et al., 2011, Chumanov et al., 2012, Orchard et al., 2012, Schache et al., 2010, Yu et al., 2008, Heiderscheit et al., 2005, Schache et al., 2009), or possibly even in the transition from late swing to early stance (Liu et al., 2017).

In late swing (Figure 2.25) the hip reaches maximum flexion (50-60^0) (50% of total range), the knee extends (Mann, 2011) and the hamstring act eccentrically working negatively to decelerate the limb (Figure 2.26). In early stance beginning with heel strike, the hip extends and the knee flexes (Schache et al., 2011b). In the transition from late swing to early stance simultaneous flexion and extension torques are produced at the knee and hip (Liu et al., 2017). The gluteals work with the hamstrings to extend the hip and their synergy is required for optimal hip extension and force production (Figure 2.26) (Cochrane et al., 2017).

Table 2. 12: Mechanism of HSI

(Huygaerts et al., 2020).

You will notice that the majority of research selects late swing or early stance phase as the main mechanism of HSI. *Review of 15 studies in which 10 conclude late swing phase and 3 conclude early stance phase.*

Reference	Participants	Late Swing	Early stance	Late Stance
Schache et al. (2012)	Sprinters (5 males; 2 females)	X		
Chumanov et al. (2011)	Recreational athletes (9 males; 3 females)	X		
Fiorentino et al. (2014)	Track and field athletes (7 males; 7 females)	X		
Higashihara et al. (2014)	Track and field athletes (13 athletes)	X		
Higashihara et al. (2010)	Track and field athletes (8 males)	X		
Thelen et al. (2005)	Recreational athlete (9 males; 6 females)	X		
Thelen et al. (2005)	Recreational athlete (1male)	X		
Yu et al. (2008)	Sprinters or middle distance runners (20 males)	X		X
Mann and Sprague. (1980)	Sprinters (15 males)		X	
Mann (1981)	Sprinters (15 males)		X	
Ono et al. (2015)	Track and field rugby and soccer players (12 males)		X	
Sun et al. (2015)	Sprinters (8 males)	X	X	
Liu et al. (2017)	Sprinters (8males)	X	X	
Schache et al (2009)	Australian rules football (1 male)	X		
Heiderscheit et al. (2005)	Skier (1 male)	X		

A group of 23 experts have reported that training prescription, neuromuscular and tendon properties, kinematics, kinetics and hip mechanics to be the highest risk factors to consider in running related HSI injuries (Kalema et al., 2022). On push off less hip extension is seen to be more optimal and another consideration is where the lead leg lands in front of the centre of mass (Lahti et al., 2020). This overstriding is uneconomical, causes a braking effect, extending the hamstring even further where athletes are required to provide more propulsion/energy to maintain and increase speed and makes the hamstrings more vulnerable to HSI.

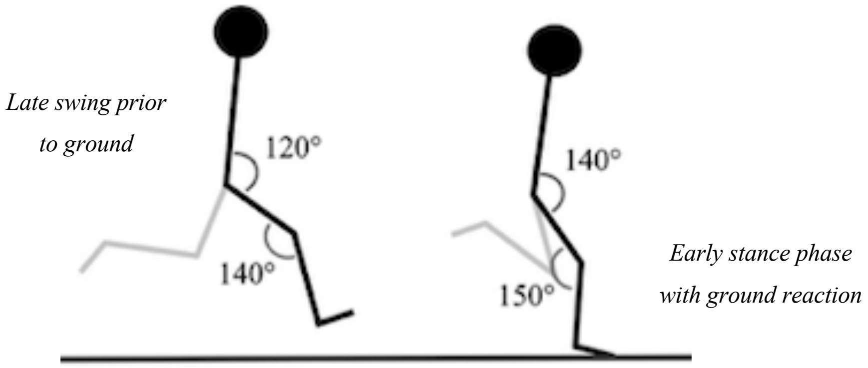


Figure 2. 25: *Late Swing and Early Stance phases (Kenneally-Dabrowski et al., 2019).*

Late swing produces the largest forces on the BFlh where it is required to elicit between 10.5-26.4N.Kg^{-1} (Kenneally-Dabrowski et al., 2019) and these peak hamstring forces occur to 100% maximum voluntary contraction during late swing (Kyröläinen et al., 2005, Higashihara et al., 2015, Higashihara et al., 2018, Whiteley et al., 2017). In a simulated running study the BFlh reaches 110% of its maximum resting length while it was also seen to have greatest excitation levels at this point (Thelen et al., 2005a). Furthermore, local muscle strain can increase by up to 29% with speed increases from 70-100% of max speed (Fiorentino and Blemker, 2014). This can also be coupled with the fact that as peak EMG levels occur during this phase there is a simultaneous strain on the muscle tendon complex where it reaches peak stretch (Higashihara et al., 2014). Interestingly a case study identified a 130ms period during late swing in which the BF reached a peak musculotendon length 12% beyond that seen in a upright posture (Heiderscheit et al., 2005). The hamstrings are required to tolerate these large forces, moments and stretching during eccentric contraction and any localised weakness within the hamstring group and the BFlh increases the risk.

During early stance a second peak in muscle activity occurs, due to maximum hip and knee flexion torques which occur in preparation for the attenuation of ground reaction forces (Mann, 1981, Mann and Hagy, 1980, Yu et al., 2008). BFlh excitation levels are greatest exceeding 100% maximum voluntary isometric contraction and two to three times greater than levels seen in both early swing and late stance (Figure 2.26) (Yu et al., 2008). This results in peak musculotendon forces of between 240-880N in early stance, lower than those seen in the late swing phase but nevertheless represent a significant strain on BFlh. The BFlh is also subjected to large tensile forces in the early stages of stance in which increases in the hip flexion angle and ground reaction forces occur at the same time (Ono, 2013). It is also seen to reach peak muscle excitation during the period from foot strike to peak ground reaction force in early stance phase for approximately 0.01s (Ono, 2013). On review of Table 2.13 it is evident that even though there are somewhat lower kinetic stresses on the BFlh during early stance, it still imposes significant stresses to elicit HSI.

Table 2. 13: *Hip and Knee kinetics with associated muscle tendon force (means) of the BFlh (adapted from Schache et al. (2012), Kenneally-Dabrowski et al. (2019), Chumanov et al. (2007)). Late swing (the most prevalent portion of the running gait cycle for HSI) has the greatest moment and produces the highest muscle tendon force.*

				80kg Athlete		
	Early Swing	**Late Swing**	**Stance**	**Early Swing**	**Late Swing**	**Stance**
Hip Moment	4.3^{f} Nm.kg^{-1}	4.2^{f} Nm.kg^{-1}	4.1^{e} Nm.kg^{-1}	344 Nm	336 Nm	328 Nm
Knee moment	1.0^{e} Nm.kg^{-1}	1.8^{f} Nm.kg^{-1}	3.6^{e} Nm.kg^{-1}	80 Nm	144 Nm	288 Nm
Muscle-tendon force	-	36.4 N.kg-^{1}	28 N.kg-^{1}	-	2912 N	2240 N

^{f} Flexion moment; ^{e} Extension moment

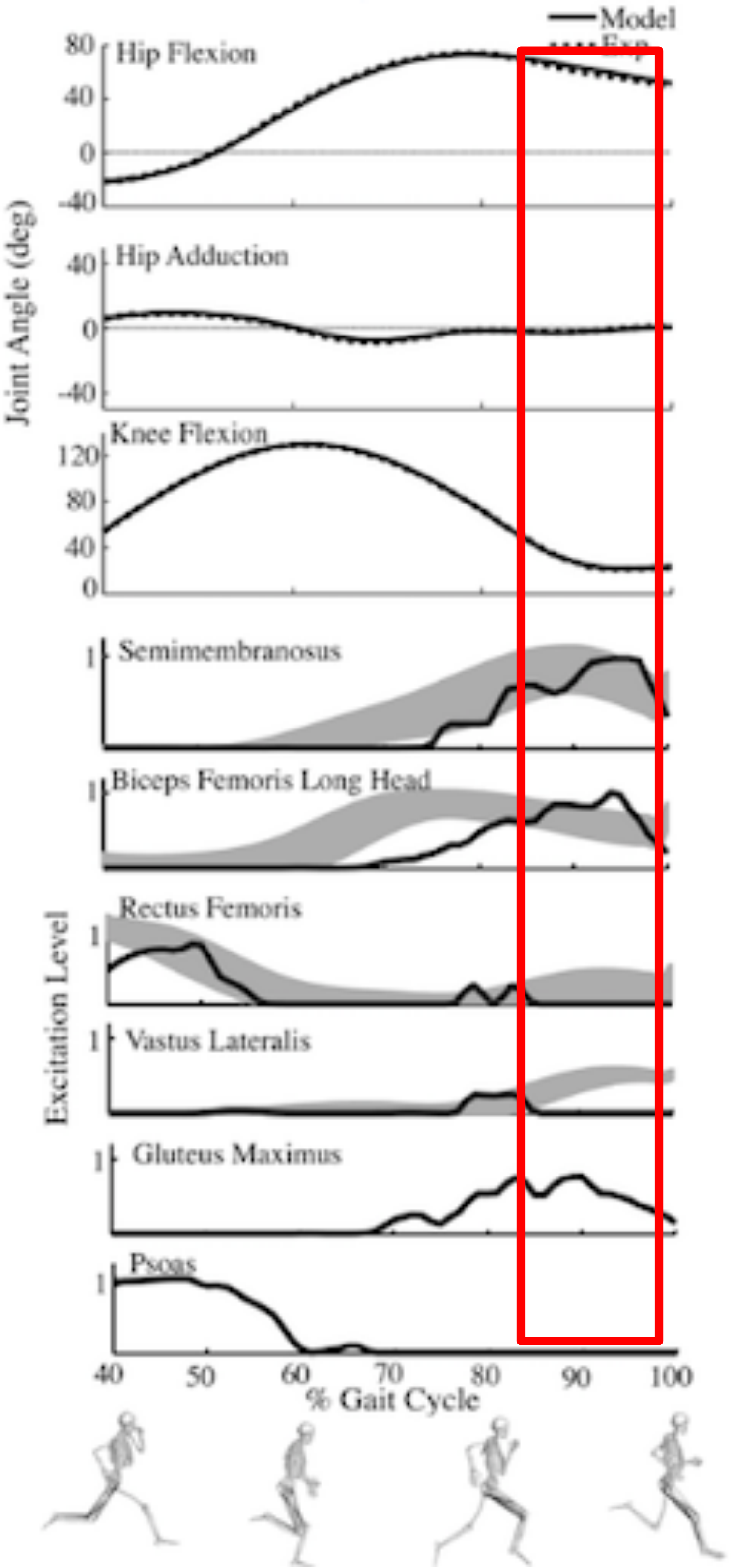


Figure 2. 26: Simulated excitation levels during the gait cycle
(Thelen et al., 2005a).

The BFlh, Semimembranosus and Gluteus maximus are highly active in late swing and prior to early stance (in Red). The hip has reached maximum flexion and now begins to extend, during which you will also notice very little change in knee angle as early stance approaches.

BFlh activity also increases disproportionately (67%) to both the ST and SM activity during high speed running which suggests it is the main propulsive portion of the hamstrings during the terminal swing phase and therefore has the highest potential for injury (Silder et al., 2010). The BFlh (74.4mm) and the SM (63.4mm) have much shorter fibre lengths than both the BFsh (130.5mm) and the ST (178.4mm) and therefore are at higher risk of injury during extension of the knee joint as fibres become elongated (Okuwaki, 2009), with shorter fibres at greater risk of injury (Butterfield, 2010, Kellis et al., 2012).

Maximal velocity and the ability to maintain high speed running for as long as possible is a key element of running performance in Gaelic football. The three main external forces are ground reaction force, gravitational force (bodyweight) and wind resistance. Players can influence ground reaction forces, contact times, flight time, step length and step frequency with technical alternations to their running patterns, furthermore these are key elements to maximum velocity and sustaining high speed running. The most relevant aspect in relation to HSI are the components of the ground reaction forces during late swing and early stance as players are vulnerable to HSI. Ground reaction forces occur in early stance whereas these do not occur in late swing (Figure 2.27).

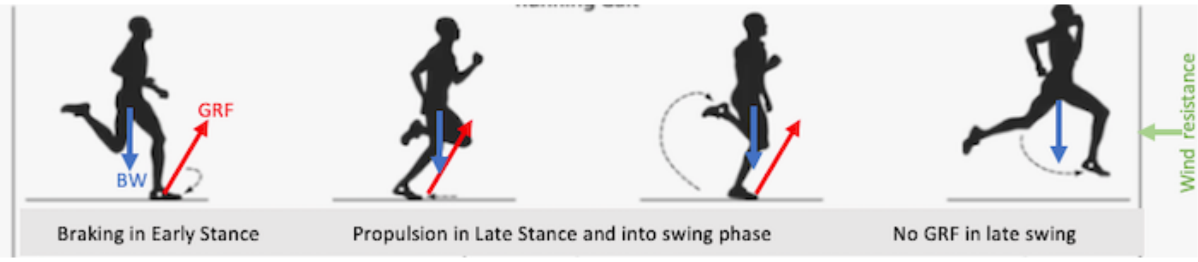


Figure 2. 27: *Free body diagram*
You will notice no ground reaction force (GRF) in late swing.

The magnitude of vertical ground reaction forces are dependent on the heel/midfoot strike (Figure 2.28). Initially on heel strike, in early stance, there is an initial ground reaction force. Players also need to generate large propulsive forces during the acceleration phase and minimise braking forces during the transitions which occur in early-late stance (Nagahara et al., 2019). The ground reaction forces which occur in early stance act posteriorly (Mero and Komi, 1986). High running performers are postulated to generate larger net anteroposterior force through the acceleration phases and less braking forces during early-late stance (Morin et al., 2015). It is widely considered that it is the large forces and moments as previously outlined that predispose to HSI in late swing and early stance. From a biomechanical rationale it is unclear as to the mechanism of HSI during late swing in which there is no external force or ground reaction force. Yet this is widely reported in 8 out of 13 studies (Table 2.12). It is difficult to ascertain as it is difficult to capture real time HSI during competitive play and particularly on grass, furthermore a recent review has concluded ambiguously, HSI is “estimated” to occur during late swing (Danielsson et al., 2020).

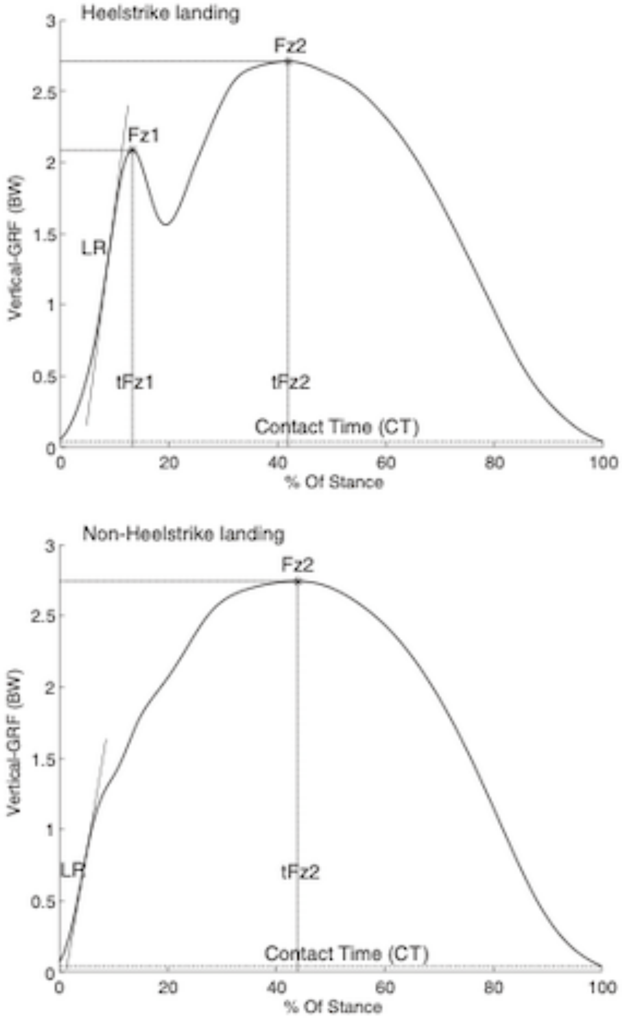


Figure 2. 28: *Ground reaction forces*

(Kluitenberg et al., 2012).

You will notice different peaks of ground reaction forces with heel strike and non-heel strike where peak GRF for both occur at 2.5-2.8 BW. You will notice in heel strike the impact peak (Fz1) (which is speed dependant) occurs in early stance (10-30ms) whereas the second largest peak occurs in mid stance (Fz2).

2.8.1 An alternative research consideration

In late swing it is widely regarded that it is the ability to withstand powerful eccentric contractions due to the negative work to decelerate the limb prior to the stance phase, as the hamstrings are required to produce large forces (Swing 89.1 N.kg^{-1} v Stance 29.6 N.kg^{-1}) (Schache et al., 2012). However, Van Hooren and Bosch (2017) proposed that the hamstrings do not lengthen during this phase and suggested a quasi-isometric contraction exists in which it is the ability to maintain isometric function that predisposes the hamstrings, to injury. However, this theory is widely debated and the proposal relies on the assumption that the hamstrings should operate in a manner similar to other muscle tissue in animal studies which has not been directly studied within the hamstrings. Nevertheless, it is worth evaluating the relationship of eccentric and isometric strength as they both may play a role in HSI during running and also as it has not been previously examined. Furthermore, muscle fascicles and series elastic elements (tendons, aponeurosis and other connective/fascial tissues) are at risk of HSI with the contracting element increasing, decreasing and recoiling to return stored energy and possibly even working isometrically prior to foot strike (Thelen et al., 2005a, Van Hooren and Bosch, 2017, Chumanov et al., 2012). The strength of the muscle and its ability to withstand eccentric and isometric force in the late swing and the transition to early stance highlights the importance of both eccentric and isometric strength for HSI prevention during running, even though isometric strength and its relationship to HSI is not widely researched nor endorsed.

2.8.2 Conclusions and Future Research

Running is the main mechanism of HSI in GF, occurs in the lead leg in late swing or early stance between 140-150° of knee extension and with the contralateral hip in extension. There is some debate as to whether this occurs in late swing or early stance and if failure of the muscle occurs due to eccentric or isometric contraction (failure of the muscle to maintain isometric force). It is clear however injury occurs in long lever positions and investigating the strength of the muscle at this point may help to provide more insight into the relationship of strength with HSI.

2.9 Main Review Findings

HSI is the most common injury in GF, proximal injuries to the BFlh the most prominent. HSI in GF is higher when compared to other field sports, doubling over the last 10 years. Strength is a strong modifiable risk factor and determines the ability of the hamstring muscles to withstand the large net peak forces (5200N) reported to be highest, at maximum running velocities, during late swing and early stance. Eccentric hamstring strength is a pre-requisite for HSI prevention and NB_{ECC} has previously been shown to be associated with HSI injury in Australian rules footballers. However, anecdotal evidence (my work with teams over the last 6 years) in GF does not indicate this to be the case and investigating pre-season and late-in-season eccentric torque in players who become injured during the playing season would resolve this debate (Study 1). Given this query, and, also, due to the lack of consensus within the literature regarding the association of strength and HSI, it is worthwhile to re-examine existing methods of isometric and eccentric testing. Isometric testing has been linked to HSI but information is scarce. Testing is also undertaken in a prone position as oppose to the upright posture required for locomotion. Engaging an isometric test position which better simulates the joint posture in late swing/early stance (mechanism of HSI in running) may help to increase its sensitivity for the detection of any underlying weaknesses (Study 2) and further isolating a unilateral testing method may provide more sensitivity to HSI (Study 3), particularly if it is more similar to running posture which would simulate the role of the gluteal with the hamstrings. It is reported IKD is widely used for eccentric assessment but there is debate surrounding errors of measurement which may disguise the weaknesses/deficits associated with HSI. This should be good and normal practice, however this is not the case and addressing these errors with a more novel IKD method which addresses the alignment of the central axis (aligning it under isometric contraction in mid-range), mode of testing (assessing eccentric strength during passive mode), testing eccentric strength in isolation and adopting testing speeds in which the user can elicit a maximum contraction throughout the full range of testing may increase the accuracy of torque measurements (Study 4). Contrary to strength testing, it is widely accepted underlying muscle architecture (L_f and θ_p) are related to HSI. L_f lengths are not accurate within the literature, as they have been estimated rather than directly determined. Addressing this by directly determining L_f has not been previously reported in GF (Study 5). Finally the use of isometric data to safely assess grading and classification of HSI would aid clinicians as no such data exists (Study 6).

STUDY 1

Pre-season and Late In-season Eccentric Strength (Nordbord) and Relationship to Hamstring Injury in Club Gaelic Footballers.

3.1 Introduction

Low eccentric knee flexor strength is a potential risk factor for future HSI and more research is advocated in this area (Croisier et al., 2002, Petersen et al., 2011), particularly given the debate surrounding NB_{Ecc} strength and HSI, as discussed in Chapter 2. Data is reported in force (N) rather than torque (Nm) which does not take into account the length of the lever in generating the force during the NB_{Ecc} assessment. Consequently, it is not possible to compare groups of players with different limb lengths and prior to undertaking this study in January 2019 there was very little if any data in relation to GF. This investigation will consider individual limb lengths by calculating the torque generated about the knee joint for an improved evaluation of NB_{Ecc} strength.

Therefore, the purpose of this study was to compare pre-season and late in-season NB_{Ecc} torque between injured and un-injured players. The objectives were to examine (1) pre-season eccentric torque in the injured versus un-injured limbs in players who experienced HSI later on in the playing season (2) late in-season eccentric torque in the injured versus uninjured limbs in players who had suffered HSI during the playing season (3) whether those players that became injured during the season had weak eccentric strength in pre-season in comparison to those players who did not become injured (4) to determine bilateral hamstring imbalance and the effect of prior hamstring injury, age and eccentric torque on the relative risk of future HSI.

3.1.1. Hypothesis (For objective 3)

- Pre-season eccentric torque is lower in the involved versus un-involved limbs in players who sustain a HSI during the playing season.

- Late in-season eccentric torque is lower in the involved versus uninvolved limb in players who sustain a HSI during the playing season.
- Bilateral hamstring imbalances, prior hamstring injury, older players and lower levels of eccentric torque increase the relative risk of future HSI.

3.2 Methods

3.2.1 Participants and study design

This was the first of all studies and was undertaken pre Covid 19 outbreak in early-late 2019. A total of 117 players were tested for maximal eccentric strength in preseason (January and February 2019) and 96 players were tested late in-season (September and October 2019), from 6 clubs (5 Senior Clubs and 1 Junior club) from the Connacht and Ulster regions which were originally recruited for this study. Of the two testing groups, 67 players were tested both in pre-season and late in-season.

Prior to testing each player was provided with an injury questionnaire modified from The Oslo Sports Trauma Research Centre questionnaire (Clarsen et al., 2014) and detailed injury history and testing procedures.

Ethical approval was granted by John Moore's University Liverpool ethical committee (21/SPS/005). All players were above 18 years of age, informed of the procedure, screened prior to testing for injury and provided consent.

Players were excluded that had sustained any lower limb injury less than 3 weeks prior to testing or had a current injury that prevented them from performing the tests.

3.2.2 Eccentric strength assessment

Nordbord testing system™ was used which has a moderate to high retest reliability of (ICC=0.83-0.90) (Opar et al., 2013b). Participants performed 5-10 minutes of dynamic warm-up and were given a visual demonstration of how to perform the Nordic hamstring exercise by the tester. They were instructed to kneel on the pad of the Norbord and their ankles were placed into the instrumented (load cells) restraints of the Nordbord device, with the lateral malleolus immediately superior to the restraints. Force data was stored on a tablet device (iPad, Apple Inc.). The knee position was recorded on the integrated pads with the ankle hooks at 90^{o} to the lateral malleolus. Limb segment length was measured from the lateral malleolus (Peroneal tubercle), palpated to the lateral joint line of the knee. A demonstration of the test was provided. Participants were instructed to gradually lean forward as slowly as possible, resisting the falling movement with both limbs by pulling into ankle hooks, with their hands across their chest, while maintaining their trunk and hips in a neutral position through the entire movement (Buchheit et al., 2016).

Each participant performed a minimum of 1 set of two trial repetitions at 80% maximum effort, with emphasis on performing the exercise with the appropriate technique. If the instructor was not satisfied with the standard of execution of the exercise the participant performed a second set of 2 repetitions. They were instructed the test was a maximal test and to maintain contraction for as long as possible. They then performed a set of 3 maximal effort repetitions of Nordic curls exercise with 30 seconds recovery between each repetition. Torque was calculated using the formula: Torque = force x perpendicular distance, where force is the maximal force recorded during the NB_{Ecc} and distance is the lever length (lateral malleolus to the knee joint (as above). Relative force and torque were calculated by dividing the absolute score by body mass (Roe et al., 2018a).

3.2.3 HSI reporting

For this study a hamstring injury was classified as acute pain in the posterior thigh and one which involved time loss to training or games. Players completed a standard injury report which detailed the involved limb, the location of the injury, the duration of return to training or games and the mechanism of injury.

The maximum peak force for each limb, left and right was recorded from the three trials. Forces were reported in absolute units (N) to compare to previous studies and as a torque in order to normalise for shank length and force was expressed in relative to body weight.

3.2.4 Data analysis

Data were analysed using SPSS software package V.18.0 (SPSS Inc, Chicago, Illinois, USA). The mean and SD of age, time loss due to injury and force and toque calculated for both the injured and un-injured groups was determined. Owing to the unequal group sizes, the Mann-Whitney U test was used to assess the differences between the injured and the uninjured groups for maximal force, maximal torque in both the pre and in season scores.

An independent T-test was used to compare the injured limb to non-injured limb in both the pre and in season.

Univariate analysis was performed to compare age, percentage between limb imbalances between the injured and uninjured side, eccentric hamstring strength of the injured limb. To determine univariate relative risk (RR) and 95% confidence intervals of future HSI athletes were therefore, grouped according to:

- Bilateral hamstring strength imbalance above 10, 15 and 20% in both the pre-season and in-season (to investigate the significance of various levels of bilateral hamstring strength imbalance for future injury).
- With or without previous hamstring injury
- Absolute Torque below 110, 120, 130, 140 and 150Nm
- Age, above 18.9, 19.9, 22.6, 25.5, 28.9 years (to investigate the risk of future injury to younger players, players in their mid-twenties and older players towards their thirties).

3.3 Results

3.3.1 Participant and injury details

The 67 players who were tested both in pre-season and late in-season were analysed. A total of 19 players (age, 24.7±4.5 yr) and 48 players (age, 24.5±7.2 yr) made up the injured and non-injured groups, respectively. Among the injured group there were 25 HSI. The mean time lost per hamstring injury from training or matches was 21.2 ± 12.5 days. The mechanism for injury was high speed running (which accounted for 88% of all injuries), followed by overuse (8%) and the remainder picking a football off the ground (n=1) (4%). Data in the un-injured group (N=48) were averaged as there was no difference between right and left limbs ($p>0.05$).

3.3.2 Absolute Eccentric hamstring force

In the injured group in pre-season there was no difference between the involved (285±57N) and uninvolved (289±68N) sides in force measures ($p>0.05$) however there was a significant difference in season between the involved (mean 285N, CI 95%, 229-305N) and uninvolved side following injury (mean 302N, CI 95% 248-322N, $P<0.05$). In the non-injured group, there was a significant difference in hamstring strength between preseason (mean 290, CI 95%, 235-311N, $p>0.05$) and late season (mean 305, CI 95%, 236-251N) (Table 3.1).

Table 3. 1: *Nordic hamstring exercise force variables for pre-season and late in-season (p<0.05)*

Max Absolute Force(N)			
Group	**Limb**	**Pre-season**	**Late-season**
Hamstring injury	Injured	285±57	285±64
	Non-injured	289±68	302±80*
Non injured	Average of left and right	290±62	305±57*

*Significant difference P<0.05

3.3.3 Eccentric hamstring torque

Nordic hamstring eccentric torque as described in table 3.2.

Table 3.2: *Nordic hamstring exercise Torque variables for pre-season and late in-season ($p<0.05$)*

		Absolute (Nm)		Relative ($Nm.Kg^{-1}$)	
Group	**Limb**	**Pre-season**	**Late-season**	**Pre-season**	**Late-season**
Injured	Injured	124±25	124±27	1.54±0.35	1.56±0.40
	Non injured	125±31	132±35*	1.58±0.46	1.70±0.46*
Non injured	Average of left and right	126±28	134±22	1.55±0.33	1.63±0.31

*Significant difference $P<0.05$

The effect of bilateral hamstring imbalance, prior hamstring injury, age and absolute torque on the relative risk of a future hamstring strain can be seen in Table 3.3. A hamstring strength imbalance above 10% produced a RR of 1.45 (95% CI: 1.3-2.2), 15% produced a RR of 1.55 (95% CI: 1.4-2.6) in the preseason. A hamstring strength imbalance above 10% produced a 1.4 RR (95% CI: 1.3-1.9), 15% produced a RR of 1.75 RR (95% CI: 1.2-3.1) in the late in-season. A previous hamstring injury produced a 32.88 RR. Participants above the age of 19.9 had a relative risk 1.82 of a future HSI.

Table 3. 3:*Univariate RR of HSI using eccentric strength and imbalance, previous injury, and demographic data as risk factors*

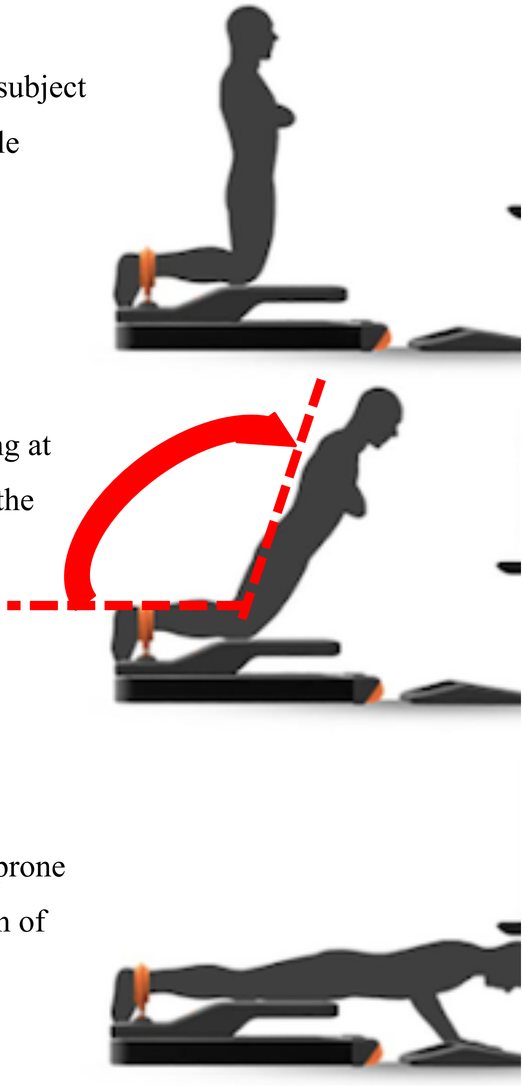
– you will notice a high RR for strength imbalances, previous HSI and Age in particular.

	N	% of HSI in Group	RR (CI 95%)	P-Value
Strength imbalance (pre-season)				
<10%	19	36.84	1.47 (1.3-2.2)	>0.05*
<15%	10	40.0	1.55 (1.4-2.6)	>0.05*
Strength imbalance (in-season)				
<10%	20	35.0	1.40 (1.3-1.9)	>0.05*
<15%	9	44.44	1.75 (1.2-3.1)	>0.05*
Previous hamstring injury				
Injured group	19	68.4	32.88	>0.05*
Non-injured group	48	2.08		
Absolute Torque Nm (Preseason)				
<110Nm	47	31.9		>0.05*
>110Nm	20	20	1.60 (1.2-2.3)	
<120Nm	34	35.3		>0.05*
>120Nm	33	21.2	1.67 (1.1-2.5)	
Age				
<18.9	65	28.8	0 (0)	<0.05
>18.9	2	0		
<19.9	55	30.35	1.82	<0.05
>19.9	12	16.66		

3.4 Discussion

The findings from the study indicate that 1) in preseason there was no difference in NB_{Ecc} torque between involved and uninvolved limbs in players who became injured later in the season 2) players (n=19) who sustained a HSI during the season have weaker NB_{Ecc} torque late in-season when comparing the involved and uninvolved limbs 3) there is no difference in NB_{Ecc} pre-season and late in-season torque in players who experienced a hamstring injury and those players who did not only in the injured limb 4) A minimum of 120Nm is suggested for injury prevention however NB_{Ecc} strength levels above 120Nm are not predictive of HSI risk. Between limb imbalance of 10-15%increases the risk of future HSI by 1.75 with players above 20 years of age having an increased risk of injury and those suffering previous injury at a significantly increased risk (33 times) of HSI.

Pre-season eccentric strength levels do not distinguish players who sustained a HSI during the playing season. We also report no NB_{ECC} bilateral imbalance in pre-season in 14 players with previous HSI from the previous season (7 of which became re-injured again later in this study). More recently, since our research began, it has also been corroborated that NB_{ECC} metrics are of little benefit in ascertaining the likelihood of future hamstring injury (Roe et al., 2020). Firstly, differences do not exist in players with HSI in pre-season. Club Gaelic footballers very often have an out of season period of 3-4 months (November-February) and during this period players undertake strength training which may help to address any underlying deficits which exist, with increases in eccentric hamstring strength reported throughout the literature, 14% (Al Attar et al., 2017, Delahunt et al., 2016). This is seen to be beneficial as it can help to reduce hamstring injuries by 50% in comparison to control groups (0.4 v 0.7 per 1000hrs) (Delahunt et al., 2016, Al Attar et al., 2017). Secondly, a possible counter argument would be that if differences do exist then perhaps this method of testing is not sensitive enough to detect these underlying weaknesses. This is a plausible argument as recurrence levels are high and one would suspect residual deficits, furthermore there is no difference in strength levels in pre-season prior to becoming injured (on a previously injured limb) later that year. This lack of sensitivity in which breakpoint generally occurs at 120^0 (Figure 3.1) (Ripley et al., 2020) (Sconce et al., 2021) and where speed of testing is not regulated maybe responsible. Consequently 1) the muscle is assessed in inner range even though injury occurs in outer ranges and 2) speed of testing will vary between each player with higher speeds perhaps reducing the breakpoint angle even further.



Start of exercise where subject is strapped in at the ankle where the load cells are

Breakpoint angle occurring at 120^0 prior to midpoint of the exercise (135^0).

The exercise finishes in a prone position with full extension of

Figure 3. 1: *Breakpoint angle on the Nordbord*

The values reported in the current study for club Gaelic footballers are lower than those reported for elite Gaelic footballers, 360N or $4.4N.kg^{-1}$ (Roe et al., 2018b), and similar to those reported for Australian football ($3.2\pm1.3N.kg^{-1}$), elite rugby union ($3.7\pm0.7N.kg^{-1}$), sub-elite rugby union ($4.0\pm0.9N.kg^{-1}$), elite cricket ($3.7\pm1.0N.kg^{-1}$) and sub-elite cricket ($3.7\pm1.0\ N.kg^{-1}$) (Opar et al., 2013b, Bourne et al., 2015, Chalker et al., 2016). Match play consists of intermittent intervals of multidirectional running and elite players cover 8889m with 18% at high speed pace >17km/h (Malone et al., 2016). The differences between elite and club Gaelic footballers may reflect the physiological demands of inter county and club football as inter county players have generally greater levels of conditioning (McIntyre, 2005).

Few studies have reported NB_{ECC} strength as torque. First of all height and weight as you would expect, influence the load applied to the knee joint during the Nordic hamstring exercise (Opar et al., 2013a) and body mass influences maximum NB_{ECC} strength. It should also be considered, that heavier players may find it more difficult to maintain longer lever positions, which may in turn influence NB_{ECC} strength values. Existing research reports an increase of 4N in maximum NB_{ECC} strength per 1kg increase in body mass (Buchheit et al., 2016). Limb length differences exist in players and it is important to consider the lever arm length as this can directly influence the torque generated about the knee. The lack of normalised data makes it difficult for practitioners to compare one player's characteristics to their peers in order to individualise interventions, if required (Chalker et al., 2016, Fox et al., 2014). Furthermore, in future it would be recommended to report relative torque values as this accounts for both limb and body mass variations and allows for future research to compare NB_{ECC} between different populations of various anthropometric characteristics.

Players in this study who had NB_{ECC} strength levels in pre-season below 120Nm (279N) were 1.7 times more likely to sustain a HSI. These RR ratios are lower than values previously reported in professional Australian footballers for pre-season with players having had a 2.7-fold increased risk of HSI with <256 N at the start of preseason. In GF as per our RR analysis we suggest an NB_{ECC} strength greater than 120Nm in preseason. It is difficult to apply cut off points as hamstring injury is multifactorial and particularly in GF as the game is physical in nature where external forces may predispose players to higher risk of injury. We should apply and use these this data more for a guide for participant rather than stringent cut offs for HSI, while also considering we have reported no differences in NB_{ECC} strength in injured players in pre-season who experience HSI during the playing season.

NB_{ECC} strength increased during the season by 6% in all limbs apart from the involved limb in those players who sustained an HSI. Time loss (21.2 ± 12.5 days) and players experiencing a de-training effect during this period, points to the requirement of more extensive rehabilitation program. Important as, 20% of elite rugby union players with strength imbalances ≥15% experienced an in-season hamstring injury and players with this characteristic were 2.4 times more at risk (Bourne et al., 2015), where we also report players with a strength imbalance ≥15% are 1.55 times more likely to sustain a HSI. More specific rehabilitation such required such as, a more protracted return to play running program at 80% max speed, prior to return to sport to ensure no bilateral differences exist.

It is also important to consider age related changes as modifiable risk factors for hamstring injuries can help direct the development of risk management programmes (Gabbe et al., 2006). Younger players are at lesser risk of hamstring injury as players above the age of 19.9 had a relative risk 1.82 of a future HSI. It has also been reported that Gaelic football players >30 years were 2.3 times at greater risk of hamstring injury compared to younger players (Roe et al., 2018b). Age-matched Gaelic football players have greater NB_{ECC} strength compared to French academy soccer players at under 17 (306N±68), under 19 (301N±72) and under 21 (299N± 52) (Buchheit et al., 2016, Chalker et al., 2016). The relationship of age and HSI with eccentric strength provides additional information on athlete risk profiling (Opar et al., 2015) and requires a more detailed analysis.

Previous injury is a strong risk factor for HSI and logistic regression revealed a significant interrelationship between age and previous HSI (Opar et al., 2013b). This is in agreement with the current study, in which previously injured players are 33 times more likely to sustain a HSI. 13 out of 19 players in the injured group had previous HSI. In rugby union (Brooks et al., 2006, Upton et al., 1996), and Australian football (Bennell et al., 1998, Freckleton and Pizzari, 2013, Orchard, 2001, Warren et al., 2010), on return to play a player is 230% more likely to sustain a future injury compared to un-injured players (Roe et al., 2018b). Only 1 of 48 players in the non-injured group had a previous hamstring injury.

Therefore the hypotheses proposed in which:

- Pre-season eccentric torque is lower in the involved versus un-involved limbs in players who sustain a HSI during the playing season is rejected.
- Late in-season eccentric torque is lower in the involved versus uninvolved limb in players who sustain a HSI during the playing season is supported.

- Bilateral hamstring imbalances in both pre-season and in-season, prior hamstring injury, older players and lower levels of eccentric torque increase the relative risk of future HSI is supported.

3.5 Summary

Pre-season screening and assessment of NB_{Ecc} torque does not distinguish players for future risk of HSI, nor does it distinguish any underlying weaknesses which may predispose to injury in the involved versus uninvolved limbs. The sensitivity of the test and its methodology was discussed as possible factors and therefore it is worthwhile considering other modes of strength assessment which may provide more sensitive measures.

3.6 Limitations

There was a range in competencies in performing a Nordic fallout during data collection given that the cohort in the study involved six different clubs. As the breaking point has been previously linked to familiarity of performing Nordics (Chapter 2) this may have affected PT output. However, this is a limitation of the methodology of the NB_{ECC} assessment. One solution and in retrospect it might be to provide participants with a familiarisation session to increase their competency in the days preceding data collection.

STUDY 2

An Investigation of a Novel Device to Assess Isometric Strength and Previous Hamstring Injury in Club Gaelic Footballers.

4.1 Introduction

Eccentric strength is well researched as high forces cause muscle fascicles to contract eccentrically when running, during late swing and are as a result vulnerable to structural damage (Van Hooren and Bosch, 2017). NB_{Ecc} does not distinguish players who have previously suffered HSI or identify players at risk of sustaining injury during the playing season (Study 1). Consequently, this method lacks sensitivity for both HSI and the identification of any residual strength deficits which may exist. More sensitive methods may highlight residual deficits as recurrence levels are high and isometric strength deficits can persist for up to three seasons following injury, despite return to full training and competition (Charlton et al., 2018a).

One area that requires further investigation is the assessment of isometric strength as it is less technical to perform and can be used safely, especially with respect to assessing acute HSI injury. Post-game isometric strength was useful in identifying a football player who was potentially susceptible to hamstring strain (Schache et al., 2011b). Isometric hamstring rehabilitation has also more recently been shown to be superior to eccentric strength training in reducing the risk of HSI (Macdonald et al., 2019). However, it is unclear if isometric strength tests can identify previous HSI and this requires further investigation (Wollin et al., 2016). We now also know that the majority of HSI during running occurs in late swing or early stance at around 30^0 of knee flexion (Kenneally-Dabrowski et al., 2019). A more novel approach of isometric testing in which the position of testing is more similar to the mechanism of injury in late swing/early stance may provide more sensitivity in detecting residual deficits in respect of future injury.

Therefore, the purpose of this study was to investigate the reliability of a novel Iso_{BI} in measuring isometric hamstring strength and following this investigate eccentric and isometric strength in relation to retrospective and prospective HSI. The objectives were three fold, firstly to examine the reliability of a novel Iso_{BI} test and then secondly compare isometric strength (ISO_{BI}) in relation to the
1) injured and un-injured limbs with previous HSI
2) players with and without previous HSI
3) dominant limb in players with and without previous HSI.

Finally compare NB_{ECC} in relation to the
1) injured and un-injured limbs with previous HSI
2) players with and without previous HSI
3) dominant limb in players with and without previous HSI.

4.1.1 Hypotheses

- Iso_{BI} test of hamstring knee flexor strength is highly reliable.
- ISO_{BI} is lower in the injured limb in players with HSI in comparison to the un- injured limb, lower in players who have previous HSI and higher in the dominant limb.
- NB_{ECC} is lower in the involved side in players with HSI, is lower in players who have previous HSI in comparison to players who do not and higher in the dominant limb of players.

Note:
This study was originally designed to test both in the preseason period (January-March 2020) and also late in-season (September-October 2020). Pre-season testing was undertaken as planned but unfortunately, with the onset of Covid-19 at the beginning of 2020 and the first National lockdown in late March 2020 it was not possible to gain access late in-season. Some lifting of Covid restrictions in August allowed a return to club sport, in a condensed club playing season during August, September, October. Games were played weekly over this three month period. Unfortunately the initial study design could not be completed (to test again late-in season and continue injury reporting throughout the season). Therefore as a result, this study became retrospective in nature and worthwhile, to continue, given that it investigated the effect of previous hamstring injury with a novel method.

4.2 Methods

4.2.1 Participants and study design

A total of 70 amateur Gaelic Football players from 4 clubs (1 Senior, 1 Intermediate and 2 Junior clubs) from the Connacht and Ulster regions were recruited for this study. All 70 players were tested in the preseason period (January to March 2020) and 45 players were tested on two separate occasions (within 3-7 days) to determine the test-retest reliability of the new bilateral isometric hamstring strength assessment approach.

Prior to testing, each player was provided with a standard injury questionnaire in order to record their previous injury history.

Ethical approval was granted by Liverpool John Moores University ethics committee (21/SPS/005). All players were 18 years old or above, informed of the procedure, verbally screened prior to testing for injury and provided consent.

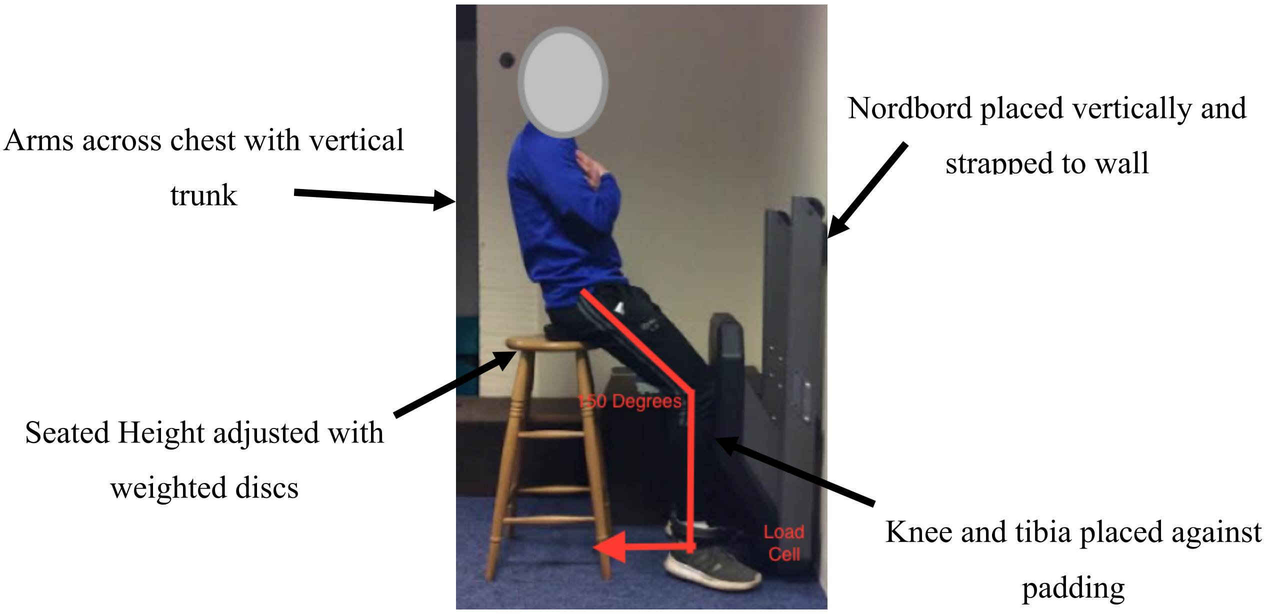
Players were excluded if they had sustained any lower limb injury less than 3 weeks prior to testing or had a current injury that prevented them from performing the tests.

4.2.2 Eccentric strength assessment

As per Study 1.

4.2.3 Bilateral Isometric strength assessment

Players were tested on two separate occasions within two days of each other during the pre-season period in which both limbs were tested simultaneously, and each limb individually recorded. The Nordbord device was placed on its side touching a wall with the ankle straps and load cells at the bottom (Fig 1). It was either secured in place and tightly strapped to a wall/squat rack using ratchet straps.



Arms across chest with vertical trunk

Nordbord placed vertically and strapped to wall

Seated Height adjusted with weighted discs

Knee and tibia placed against padding

Figure 4. 1: Iso_{BI} Strength Assessment

The knees of each leg were placed against the pad, with the ankles (malleoli) directly below the mid-point of the knee and the feet were both flat on the floor, but were lifted slightly to ensure there was no ground contact during the test (Fig 4.1). Each participant was placed into a seated position to replicate the approximate limb posture observed in the late swing/early stance phase of running (30^0 of flexion). The seat was placed 30cm away from the knee pads. Seated height was determined by creating the 150^0 angle from ankle through knee to the hip with seat height being modified by adding extra height to the stool if necessary (Fig 4.1). An investigator used a goniometer to measure this angle. The upper limb was maintained in an upright position with the shoulders directly above hips. Arms were placed across the chest to restrict their motion. The participants feet were then placed in the ankle restraints.

The participant was instructed to drive both their knees into the pad and pull both their heels maximally backwards into the hooks for 10 seconds, followed by 10 seconds recovery and then repeated three times in total. The trunk should stay upright throughout the testing protocol to minimise any possible momentum coming from the upper body. Peak torque/force was defined and recorded as the highest recorded output across all three repetitions and generally occurred in the first 3-5 seconds (Hickey et al., 2018).

4.3.4 HSI reporting

Injury data was collected from the previous season but no prospective data was collected.

4.2.5 Data analysis

Data were analysed using SPSS software package V.18.0 (SPSS Inc, Chicago, Illinois, USA). Descriptive statistics for all measures were determined using a Shapiro-Wilk test in SPSS. An Interclass correlation coefficient test was performed to determine reliability of the test, re-test for the Isometric strength testing. Reliability was assessed according to quantitative guidelines for intraclass correlations, with an ICC of less than 0.79 regarded as poor, 0.80-0.89 as moderate and above 0.90 as high (Vincent, 2005). An ICC less than 10% was set as a level of reliability (Cormack et al., 2008, Opar et al., 2013a).

Normal distribution was confirmed using the Shapiro-Wilk test. Owing to the unequal group sizes, the Mann-Whitney U test was used in pre-season to assess the differences between the injured and the uninjured groups for maximal force, maximal torque. In the injured group an independent T-test was used to compare involved to non-involved limb. Cohen's *d* ± 90% confidence intervals (90% CI) were calculated to determine for effect sizes (Hopkins, 2006). Differences were considered as trivial (<0.2), small (≥0.2), moderate (≥0.5), or large (≥0.8) (Batterham and Hopkins, 2006).

4.3 Results

4.3.1. Participant and injury details

18 out of 70 participants sustained a total of 21 hamstring strains in the season prior to testing. The mean training or match time lost per hamstring injury was 20.1±7.1 days. The dominant actions during injury occurrence were high-speed running and kicking, which accounted for 89% and 11% of hamstring strains, respectively.

4.3.2 Test-Retest Reliability

The isometric testing showed a moderate to high Reliability ICC (CI 95%) of 0.89 (CI 0.79-0.94) in terms of peak force (N). The typical error percent of the isometric testing was 7.7 % (6.9-9.7%).

Table 4. 1: *Test-retest reliability for isometric knee flexion peak force (Newtons) (n=45)*

	Test 1 (N)	**Test 2 (N)**	**Effect size**	**ICC (CI 95%)**	**Typical Error (N)**	**Typical Error (%)**
Left leg	327±56	337±63	-0.08	0.87 (0.77-0.93)	28.4 (23.5-35.9)	8.6 (7.1-10.8)
Right leg	328±55	333±66	-0.04	0.88 (0.79- 0.94)	28.0 (23.2-35.3)	8.5 (7.0-10.7)
Mean of left & right	328±51	336±60	-0.07	0.89 (0.79-.0.94)	25.41 (21.0-32.1)	7.7 (6.4-9.7)

4.3.3 Eccentric hamstring strength and torque

In the previously injured group, there was no significant difference between the involved and uninvolved sides in Absolute force, Relative force, Absolute Torque and Relative torque measures (p>0.05) (Table 4.2).

When comparing the previously injured group to the non-injured group there was no significant difference in absolute force, relative force, absolute torque and relative torque measures (p>0.05) (Table 4.3).

The dominant side was significantly stronger in the non-injured group in terms of Absolute force, Relative force, Absolute Torque and Relative torque measures (p<0.05, d=0.12-0.16). In the injured group there were 11 injuries on the dominant side and 7 on the non-dominant side both absolute force (316±50N v 276±46N) and absolute torque (137±26 v 118±17) was higher on the dominant side (Table 4.5).

4.3.4 Isometric hamstring strength and Torque

In the previously injured group, there was a significant difference between the involved and uninvolved sides in Absolute force, Relative force, Absolute Torque. Relative torque and Scaled force measures ($p<0.01$, $d=0.68$-0.74 (Table 4.2).

When comparing the previously injured group involved side to the non-injured group there was no significant difference in Absolute force, relative force and relative torque measures. ($p>0.05$). There was however a significant difference in absolute torque when comparing the injured group involved side to the non-injured group ($p<0.05$, $d=0.73$). (Table 4.3).

The dominant side (preferred kicking limb) was significantly stronger in the non-injured group in terms of Absolute force, Relative force, Absolute Torque and Relative torque measures ($p<0.05$, $d=0.14$-0.23). There seemed to be little if any difference in terms of limb dominance of the non-injured group (Table 4.5).

Table 4. 2: *Previously injured group eccentric and isometric hamstring variables.*
You will see significant differences for the ISO_{BI} in the non-involved side for all but one metric.

	Eccentric			**Isometric**		
Limb	**Involved**	**Non-Involved**	**Effect size**	**Involved**	**Non-Involved**	**Effect size**
Absolute Force (N)	307±64	322±64	0.234	281±66	332±72**	0.738
Relative force ($N.kg^{-1}$)	3.81±1.07	3.98±1.02	0.162	3.48±0.89	4.11±0.92**	0.696
Absolute Torque (Nm)	136±34	143±33	0.209	120±29	142±31**	0.72
Relative Torque ($Nm.kg^{-1}$)	1.68±.49	1.75±.45	0.149	1.49±.39	1.76±.40**	0.683
Scaled Force	5.68±1.18	5.96±1.19	0.236	5.2±1.22	6.14±1.33**	0.736
Scaled Torque	1.65±0.41	1.74±0.40	0.222	1.46±0.35	1.73±0.38	0.739

*Significant difference P>0.05 ** Significant difference P>0.01

Table 4. 3: *Previously injured group v non injured group comparing Eccentric and Isometric strength*

You will notice significant differences between the non-injured and injured limbs with effect sizes ranging between 0.5-0.7.

There were no differences between limbs in the non-injured group and limbs were grouped as a result.

	Eccentric			**Isometric**		
Group	**Injured**	**Non-Injured**		**Injured**	**Non-Injured**	
Limb	**Involved**	**Mean of L & R**	**Effect Size**	**Involved**	**Mean of L & R**	**Effect Size**
Absolute Force (N)	307±64	315±71	0.118	281±66	318±68**	0.552
Relative Force($N.kg^{-1}$)	3.81±1.07	3.84±0.83	0.115	3.48±0.89	3.89±0.82**	0.48
Absolute Torque (Nm)	136±34	136±32	0	120±29	142±31*	0.733
Relative Torque ($Nm.kg^{-1}$)	1.68±0.49	1.66±0.35	0.047	1.49±0.39	1.69±0.38**	0.519
Scaled Force	5.68±1.18	5.73±1.23	0.041	5.2±1.22	5.80±1.22	0.492
Scaled Torque	1.65±0.41	1.62±0.34	0.080	1.46±0.35	1.65±0.37	0.528

* Significant difference P>0.01**; **Significant difference P>0.05;

Table 4. 4: Non injured group comparing dominant v non-dominant.

Y*ou will notice significant differences between the dominant and nondominant limbs with effect sizes ranging between 0.1-0.2 for both eccentric and isometric strength.*

	Eccentric			**Isometric**		
Limb	**Non-Dominant**	**Dominant**	**Effect size**	**Non - Dominant**	**Dominant**	**Effect Size**
Absolute Force (N)	309±74	320±73*	0.150	310±73	326±69*	0.225
Relative Force ($N.kg^{1}$)	3.78±0.84	3.91±0.86*	0.152	3.80±0.89	3.98±0.82*	0.14
Absolute Torque (Nm)	134±33	138±33*	0.121	135±34	142±35**	0.206
Relative Torque ($Nm.kg^{1}$)	1.62±.36	1.68±0.37*	0.164	1.65±.40	1.73±.40*	0.20
Scaled force	5.64±1.25	5.83±1.29	0.15	5.66±1.33	5.94±1.22	0.227
Scaled Torque	1.59±0.34	1.65±0.36	0.171	1.62±0.39	1.70±0.39	0.205

*Significant difference P>0.05 ** Significant difference P>0.01

Table 4. 5: *Injured group comparing dominant v non-dominant.*
You will see no differences in either eccentric or isometric strength.

	Eccentric		**Isometric**	
	Non-Dominant side injury (N=7)	**Dominant side injury (N=11)**	**Non-Dominant side injury (N=7)**	**Dominant side injury (N=11)**
Absolute Force (N)	276±46	316±50	294±76	284±74
Relative force (N.kg^1)	3.28±0.66	3.96±0.73	3.50±1.01	3.54±0.97
Absolute Torque (Nm)	118±17	137±26	126±31	124±34
Relative Torque (Nm.kg^1)	1.41±0.25	1.72±0.37	1.54±0.43	1.50±0.41
Scaled Force	4.91±1.00	5.91±1.09	5.30±1.45	5.23±1.51
Scaled Torque	1.38±0.24	1.68±0.36	1.51±0.43	1.47±0.4

Asymmetries were greatest for the ISO$_{BI}$ and very little difference in any of the NBECC ratios (Table 6.6).

Table 4. 6:*Asymmetry ratios of Injured and non-injured group.*
You will notice greatest asymmetries in ISO$_{BI}$ injured group.

	Injured group (Injured v Un-injured limb)	**Non-Injured group (Dominant v non-dominant)**
ISO$_{BI}$	0.85 ± 0.14	0.96 ± 0.13
NB$_{ECC}$	0.95 ± 0.13	0.96 ± 0.12

In players with previous HSI all but one player had isometric strength below 150Nm (Figure 4.2).

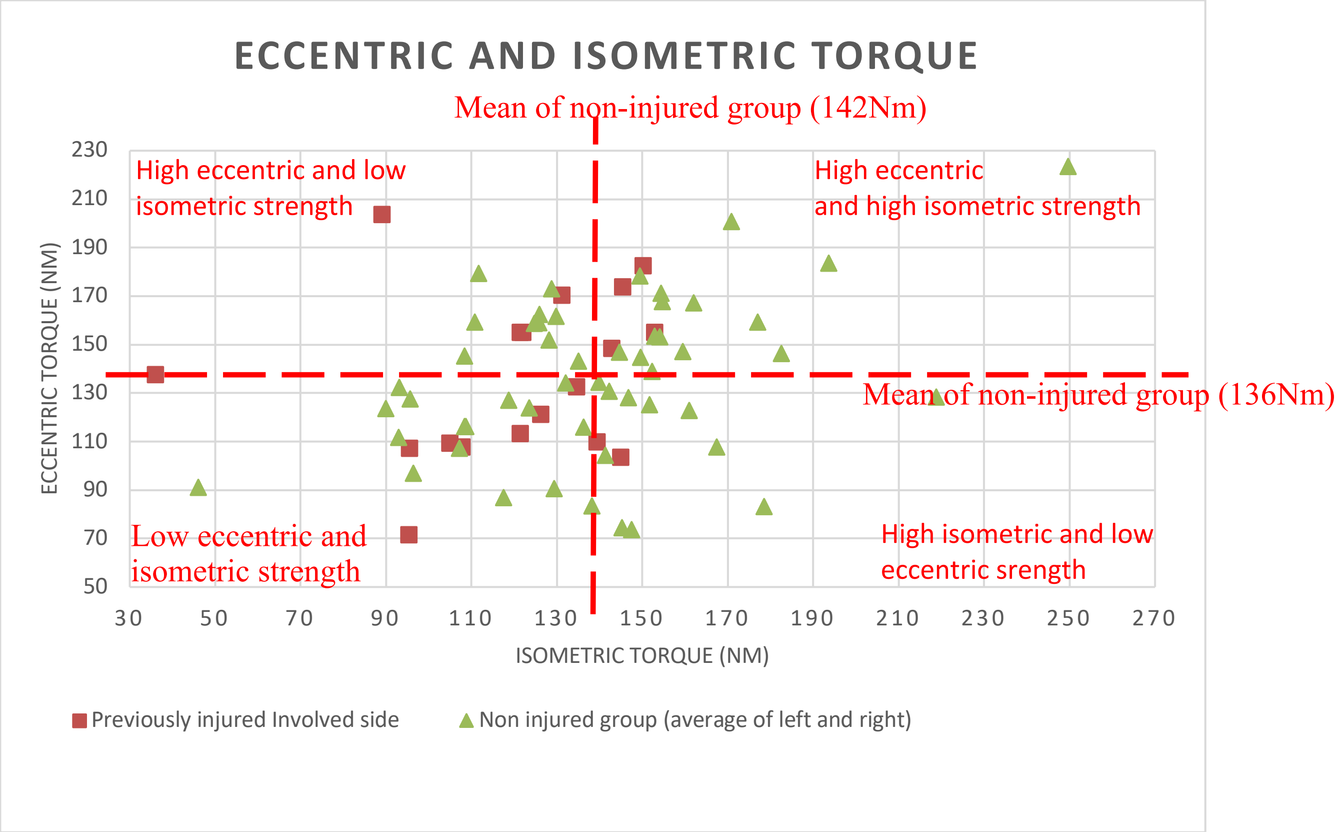


Figure 4. 2: *Eccentric and Isometric torque of injured v non-injured groups.*

You will notice that only 1 previously injured players exhibits isometric strength levels above 150 Nm.

4.4. Discussion

The purpose of this study was to determine the reliability of a novel $\mathrm{Iso_{BI}}$ testing of the knee flexors and compare these isometric measures with $\mathrm{NB_{Ecc}}$ strength measurements in Gaelic football players with previous hamstring strain injuries. The findings indicate 1) A moderate to high reliability for $\mathrm{Iso_{BI}}$ testing 2) In previously injured footballers there is a underlying $\mathrm{Iso_{BI}}$ strength imbalance and low $\mathrm{Iso_{BI}}$ strength is a reasonable indicator of previous HSI whereas $\mathrm{NB_{Ecc}}$ strength imbalances are not 3) The dominant side is the most commonly involved side in HSI and in the non-injured group both $\mathrm{NB_{Ecc}}$ and $\mathrm{Iso_{BI}}$ strength is significantly stronger.

There is moderate to high reliability for $\mathrm{Iso_{BI}}$ of 0.89, ICC=0.79-0.94 (Cohen, 1992, Vincent, 2005). This is similar to other hamstring isometric strength testing for both an externally fixed dynamometer (ICC 0.74-0.93) (Wollin et al., 2016) and force plate (ICC=0.86-0.95)

(McCall et al., 2015a). Isometric strength can be determined using the current system, test protocols and procedures reliably to assess knee flexor isometric strength.

MVIC has been shown to identify those potentially susceptible to hamstring strain (Schache et al., 2011b) and we report Iso_{BI} force and torque all differed significantly with a moderate effect size ($p<0.01$, $d=0.68$-0.74) between the injured and uninjured limbs in players with previous hamstring injury. Absolute torque was also significantly lower in players with previous HSI in comparison to their non-injured peers. Reductions in isometric strength increase the risk of HSI by 82% for every unit decrease normalised to body mass and deficits can persist for up to three seasons following injury (Charlton et al., 2018a). There were no differences noted in NB_{ECC} strength between the involved and un-involved sides in players with previous HSI. Similarly, to study 1 our results support previous research that NB_{ECC} pre-season strength does not distinguish players who previously suffered HSI in Gaelic football. Underlying strength issues may still remain as previous injury is a strong risk (Opar et al., 2013b, Warren et al., 2010), on returning to play Gaelic footballers are 230% more likely to sustain a future injury compared to un-injured players (Roe et al., 2018b). As we have indicated in study 1, previous injury is still the strongest risk factor where Gaelic players are 33 times more likely to sustain an HSI. Therefore, one would assume strength deficits still exist and it may be that Iso_{BI} testing is more sensitive to detecting residual or underlying weaknesses than NB_{ECC}. Iso_{BI} test assessed muscle function in a long lever 150° position where as the NB_{ECC} does not test in this joint position/muscle lengths as a break point angle has been reported to occur in high performers at 126±6° and low performers 103±7° (Ripley et al., 2020). Running injuries account for 73% of HSI in Gaelic football (Roe et al., 2018b) Elite GF players were found to cover 8889m with 18% at a high speed pace exceeding >17km/h (Malone et al., 2016) and exposure to high speed running in Australian rules football increases HSI by 3.3 times (Ruddy et al., 2018). In running HSI occurs in long lever positions in late swing phase/early stance (Chumanov et al., 2012, Orchard et al., 2012, Schache et al., 2010) in which the knee extends with maximum hip flexion (Schache et al., 2011b) and peak hamstring forces occur to 100% maximum voluntary contraction (Higashihara et al., 2017) with a large increase in BF muscle tendon unit length (112%) (Nagano et al., 2014). The long lever testing position of our Iso_{BI} assessment places the hamstrings in a position similar to late swing/early stance and at a length where any underlying weaknesses can be detected and more crucial to injury prevention. In addition peak isometric muscle force has been found to occur at longer muscle lengths (Kong and Burns, 2010) whereas NB_{ECC} maximum scores are produced in inner ranges and may explain the greater sensitivity of ISO_{BI}.

NB_{ECC} preseason torque in those players without previous HSI (136±32Nm or 1.66 ± 0.35 $N.kg^{-1}$) is similar to that previously reported in study 1. Pre-season strength is important at club level as players who had NB_{ECC} strength levels below 120Nm were 1.7 times more likely to sustain a HSI (Study 1), currently 50% of players who became injured are below this cut off value. As ISO_{BI} is more sensitive we report a trend towards low Iso_{BI} strength in pre-season in which injured players has significantly lower isometric strength and where all players below 150Nm/1.82 $Nm.kg^{-1}$ in preseason went on to sustain HSI during the playing season. This sensitivity is important in pre-season as it highlights players who may require pre-habitation to minimise risk of HSI prior to the start of the season.

NB_{ECC} and Iso_{BI} strength in the non-injured group is slightly stronger in the dominant limb ($P>0.05$, df= 0.1-0.2). It has been speculated that football players with a preference for a single leg can develop asymmetry between their dominant and non-dominant sides and therefore a greater response to training and competition is seen (Bjelica et al., 2013). Soccer players in particular develop bilateral deficits in relation to their kicking or dominant side and are specific to the activities of sprinting (change of direction), jumping and kicking (Blache and Monteil, 2012). Usually players have a preferred side, particularly when kicking and jumping (preferred leg to jump off), but may also at times load a preferred limb when pivoting, twisting or changing direction. Bilateral strength deficits in which the dominant side (preferred kicking leg) becomes more fatigued following match play (McCall et al., 2015a) may also account for the higher incidence of injury on the dominant side.

Therefore the hypotheses proposed in which:

- Moderate to high reliability for Iso_{BI} test of hamstring knee flexor strength is supported.
- ISO_{BI} is lower in the injured limb in players with HSI in comparison to the un- injured limb, lower in players who have previous HSI and higher in the dominant limb is supported.

- NB_{ECC} is lower in the involved side in players with HSI, is lower in players who have previous HSI in comparison to players who do not and higher in the dominant limb of players is rejected.

4.5 Summary

In summary we report a high reliability for Iso_{BI} testing which detects Iso_{BI} strength imbalances in players with previous HSI and low Iso_{BI} strength is also a reasonable indicator of previous HSI whereas NB_{Ecc} is not. Iso_{BI} and isometric strength in particular requires further investigation in respect of HSI.

4.6 Limitations

- Access to cohort during late in-season due to the restrictions around Covid 19 limited the study, in terms of investigating prospective data.
- The seat height was adjusted to attain 150^0 of knee extension. Although the subject remained stable on the seat with the added height a more bespoke seat with vertical adjustments to the height would be an advantage and eliminate any possibility of instability while being seated for the test.
- The ISO_{BI} is knee dominant (feet off the floor), isolates the hamstrings and therefore does not take into account the role of the gluteal and hip which are involved in the mechanism (running) of HSI.
- ISO_{BI} provides bilateral assessment of both limbs simultaneously. Therefore, there is a possibility that this method could possibly allow for compensations during which neural crossover may facilitate the stronger limb compensating for the weaker limb. This technique does not also take into account the position of the contralateral limb during the running gait cycle. Addressing both these issues might increase the sensitivity of testing to HSI.

STUDY 3

Reliability of a Novel Test to Assess Unilateral Isometric Hamstring Strength.

5.1 Introduction

Pre-season Iso_{BI} hamstring strength is significantly weaker in the injured limb in comparison to the non-injured limb, in players who suffered have HSI in the previous season (Study 2). This novel hamstring assessment is bilateral with both limbs in 30^0 of knee flexion. It is also worth expanding this concept by considering the position of the contralateral side as the placement of the contralateral hip into extension simulates the mechanism of injury in which the contralateral hip is extended to $20\text{-}30^0$ during late swing (Kenneally-Dabrowski et al., 2019, Chumanov et al., 2012). Extending the contralateral hip (increases the angle between the hips) increases the moment about the hip and activates the contralateral gluteal, which has a key role in hip extension (Figure 5.1). Furthermore, testing unilaterally would prevent any potential neural crossover or compensations from a more dominant or non-injured limb and thus eliminate any potential for limbs to compensate.

Figure 5. 1: *Contralateral limb during late swing.*

The aim of this study to investigate the reliability of a novel approach Iso_{UNI} in measuring isometric hamstring strength and determine its test-retest reliability.

5.1.1 Hypothesis

Isometric unilateral strength (Iso_{UNI}) is highly reliable in measuring isometric strength.

5.2 Methods

5.2.1 Participants and study design

A total of 35 non-elite club Gaelic Football players from the Connacht region were recruited for this study. All 35 players were tested in-season (March 2020) on two separate occasions to determine the test-retest reliability of the new unilateral isometric hamstring strength assessment approach.

Screening, ethical approval and pre-test questionnaire as per studies 1 & 2.

5.2.2 Unilateral strength assessment

Iso_{UNI} assessment was used to determine maximal hamstring isometric force using the load cells of the Nordbord testing system™ which was modified to test for one limb at a time. Participants performed a 1-2 minutes of dynamic warm-up and were given a visual demonstration of how to perform the unilateral isometric pull by the tester. Unilateral strength assessment began randomly with either the right or left limb. The participant was instructed to maintain a upright posture and held onto a vertical bar for support which was positioned 1m from the ground directly in line with the vertical pads of the Nordbord (Figure 5.2). The involved knee was then placed on a bench, initially 60cm away from the front pad of the nordbord (to initially setup the athlete) and 50cm in height, by aligning the pole of the patella with the outer aspect of the bench and the non-involved knee placed tightly against a 30^0 wedge. This was to achieve 150^0 at the knee, while the ankle was strapped into the ankle restraint with the foot flat on the ground (supported for setup and lifted/non-weightbearing for testing). This was checked via a goniometer in which the goniometer was aligned with the palpated lateral joint line of the knee and both hands of the goniometer were centred with the femur and tibia to verify 150^0. The involved/contralateral side was then adjusted to extend the hip to 20^0 by adjusting the bench from its initial setup position (60cm from the Nordbord). This was achieved by positioning the goniometer with the centre of the hip joint and aligning the axis with the vertical trunk. 20^0 hip extension was then measured by moving the bench towards or away from the Nordbord until this angle was attained while also keeping the lateral pole of the patella on the outside of the bench.

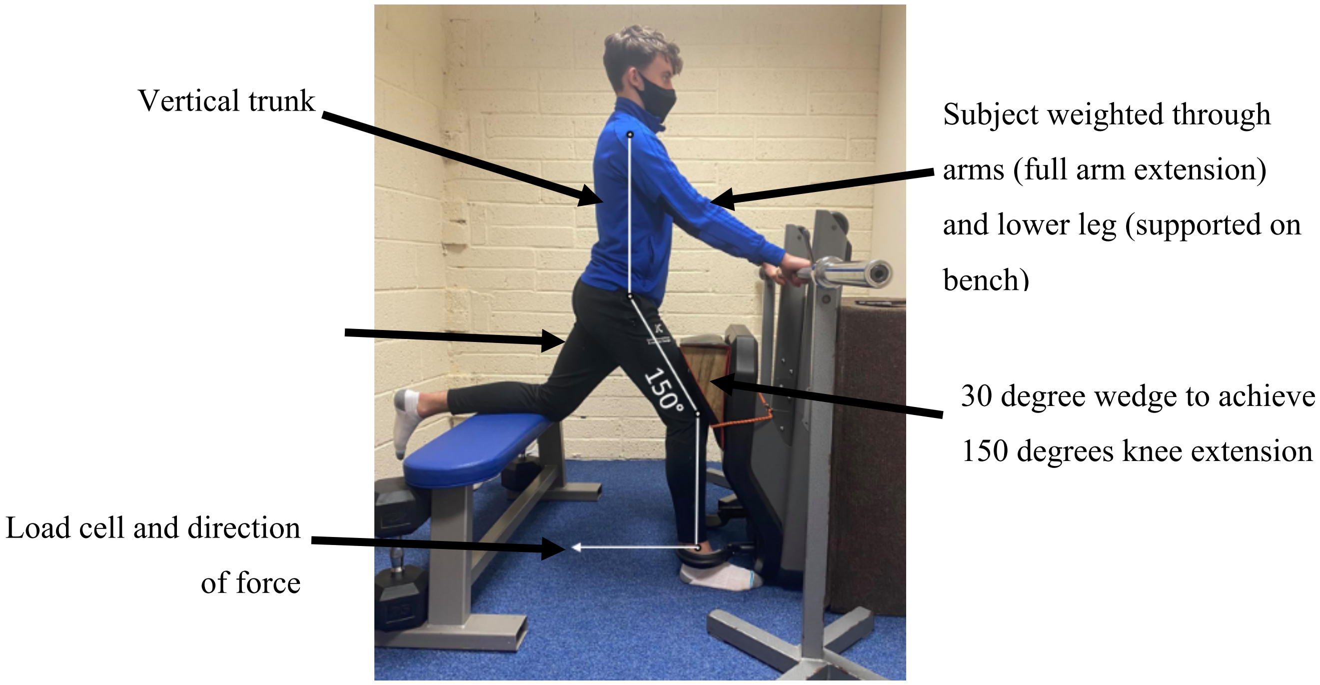


Figure 5. 2: Uni-lateral Isometric Strength Assessment

The test began by instructing the participant to stay in a upright position, unweighting the body by holding onto the front bar and lifted the foot slightly off the ground. The participant was instructed to perform a maximal repetition for 5 secs by pulling the ankle restraint away from the Nordbord rested for 20 secs and this repetition was repeated again. The involved side was then tested by performing the same setup and the protocol repeated. Three sets of two maximal repetitions were recorded for each limb and the maximum score was recorded on a tablet device (iPad, Apple Inc.). All players performed the testing on two separate occasion all within 7 days of each other.

5.2.3 Data analysis

Data were analysed using SPSS software package V.18.0 (SPSS Inc, Chicago, Illinois, USA). Descriptive statistics for all measures were determined using a Shapiro-Wilk test in SPSS. An Interclass correlation coefficient test was performed to determine reliability of the Isometric strength testing. Reliability was assessed according to quantitative guidelines for intraclass correlations, with an ICC of less than 0.79 regarded as poor, 0.80-0.89 as moderate and above 0.90 as high (Vincent, 2005). An ICC less than 10% was set as a level of reliability (Cormack et al., 2008, Opar et al., 2013a).

5.3 Results

5.3.1 Test-Retest Reliability

The isometric testing showed a moderate to high Reliability ICC (CI 95%) of 0.9 (CI 0.8-0.95) in terms of peak force (N). The typical error percent of the isometric testing was 4% (3.1-5.1%).

Table 5. 1: *Test-retest reliability isometric knee flexion peak force (Newtons) for all 35 players.*

	Test 1 (N)	Test 2 (N)	Effect size	ICC (CI 95%)	Typical Error (N)	Typical Error (%)
Left	308±42	312±43	0.094	.893 (.800-.945)	13.79 (11.16-18.07)	4.4 (3.6-5.8)
Right	316±49	306±47	0.208	.859 (.726-.928)	17.20 (13.91-22.53)	5.5 (4.5-7.2)
Mean of left and right	312±41	309±38	0.076	.909 (.829-.953)	12.02 (9.72-15.75)	3.9 (3.1-5.1)

5.4 Discussion

The purpose was to determine the reliability of an Iso_{UNI} in measuring unilateral isometric strength. A moderate to high reliability was reported for isometric testing of 0.88, ICC=0.83-0.96 with a unilateral method for knee flexor strength using the Nordbord testing system™ in a cohort of 35 club Gaelic footballers. The test procedures as undertaken in the current study have good reliability (Cohen, 1992, Vincent, 1999). This is similar to other hamstring isometric strength testing devices (Wollin et al., 2016; Mc Call et al., 2015) and also similar to Study 2. Typical error of measurement (4%) is lower than unilateral testing for the Nordbord (10%) (Opar et al., 2013a).

Therefore the hypotheses proposed in which:

- Isometric unilateral strength (Iso_{UNI}) is moderate to high in measuring isometric strength is supported.

5.5 Summary

Iso_{UNI} can be determined using the current system, test protocols and procedures in order to reliably assess unilateral knee flexor isometric strength. This method requires further investigation and its sensitivity to HSI is examined in more detail in Chapter 6.

5.6 Limitations

- The Nordbord (placed vertically) needs to be strapped tightly to a stationery object to ensure there is no movement during testing. Also, the support bar in which the participant is weight bearing through is required to be on a smooth flat surface to ensure it is stable. One solution would be a custom-built rig to incorporate all aspects of the rigging.
- It is unclear from this study as to the relationship of ISO_{UNI} to HSI and investigating a cohort of players with previous HSI would be beneficial.

STUDY 4

Isometric, Isokinetic and Eccentric Nordbord Strength and its Relationship with Retrospective and Prospective HSI in GF.

6.1 Introduction

NB_{Ecc} pre-season screening using does not distinguish any underlying weaknesses which predispose to future HSI (Study 1). NB_{ECC} forces are similar to ISO_{BI} forces in non-injured limbs, however in previously injured footballers there is an underlying Iso_{BI} strength imbalance whereas NB_{Ecc} strength imbalances are not evident (Study 2). Low ISO_{BI} strength levels were also a reasonable indicator of previous HSI and a more novel unilateral isometric test (ISO_{UNI}) but have not been related to future HSI. IKD is another form of strength testing where various ratios are associated with the risk of HSI (Chapter 2). Given the debate surrounding isometric and eccentric strength and HSI it would be useful to combine a number of modes of strength assessment to investigate whether any weaknesses are evident among those with HSI.

IKD research is conflicting where methodological issues are a factor as errors associated with movement and misalignment of the knee joint range creates torque errors of between 10-19% and more novel approaches are required as a result with fluctuations in torque production as a result (Arampatzis et al., 2004, Kaufman et al., 1995, Tsatalas et al., 2010). One solution is to place the lever arm in mid-range strapping and aligning the knee during an active isometric contraction to minimise translation and oscillation of the dynamometer head from the centre of axis during assessment (Baltzopoulos et al., 2012). This ensures that when peak torque occurs the limb is aligned with the dynamometer head. In order to achieve this however each muscle group must be aligned under isometric contraction and therefore individual muscles are required to be tested in isolation (particularly during eccentric testing). Mode of testing is also a consideration as in isokinetic mode during eccentric testing, the participant is required to forcefully contract isometrically to begin movement of the dynamometer head and then changes to a maximal eccentric contraction as they extend through range. Testing in passive mode is more suitable as it resolves this issue as there is no need for an maximum voluntary isometric contraction to begin the movement (flexion to initiate eccentric assessment of the hamstrings) and a full eccentric contraction can be maintained throughout the testing range. The testing velocity is a further consideration and 60^0/sec is recommended (Baroni et al. (2020), as it ensures the subject has an adequate window of constant angular velocity to elicit a true maximum contraction in a greater arc of testing (Chapter 2). Therefore, relatively slow joint angular velocities may be more accurate in highlighting ratio deficits even though they do not represent the high joint velocities during sprinting (Orchard et al., 1997). Addressing these issues with a novel IKD methodology by aligning under contraction and testing eccentrically in passive mode may help to reduce the errors of measurement associated with testing.

This study was designed to be both retrospective and prospective (see note) and the aim of which was to investigate IKD, isometric and eccentric imbalances in players with HSI. Given that there is widespread debate about the application of these modes to testing this battery of testing may help clarify where any underlying deficits or weakness exist and in which modes of testing, in relation to previous and future HSI. The objectives were therefore was to examine 1) the reliability of a novel IKD methodology 2) whether differences exist in ISO_{BI}, ISO_{UNI}, NB_{ECC} strength between the involved and un-involved limbs of players with HSI and between injured and uninjured groups 3) whether differences exist in IKD peak torque concentric and eccentric strength between the involved and un-involved limbs of players with HSI and between injured and uninjured groups 4) whether differences exist in IKD ratios (opposite to opposite hamstring and functional ratios) involved and un-involved limbs of players with HSI and between injured and uninjured groups.

6.1.1 Hypotheses

- A novel IKD methodology is highly reliable.
- ISO_{BI}, ISO_{UNI}, NB_{ECC} strength is lower in the involved limb of players with HSI and injured players are weaker compared to their uninjured counterparts.
- IKD concentric and eccentric peak torque is lower in involved limb of players with

HSI and players are weaker compared to their uninjured counterparts.
- IKD ratios are lower in the involved limb in players with HSI and lower in the injured group compared to the uninjured group.

Note:
This study was originally designed to test both in the preseason period of January 2021 and late in-season period which would have normally been August 2021, however it began in July 2021 following the second national COVID-19 lockdown and following the easing of restrictions. It was re-designed to track the HSI incidence throughout the playing season (from July) and also re-test late in-season (November). Usually, the GAA season is over 8+ months in duration, however it is worth noting at this stage due to government advice and policy a truncated 3-month season ran during September, October and November. First of all it was also not possible to gain access to the GF teams late in-season for re-testing due to these Covid-19 restrictions. Secondly, during this period there were only 6 hamstring injuries detected during the playing season due to a reduced number of games. Data was analysed prospectively (with no signifiance statistically) and due to the low number of injuries this data is not reported here. Therefore this study became retrospective rather than prospective.

6.2 Methods

6.2.1 Participants and study design

A total of 49 amateur Gaelic Football players from 4 clubs, 2 Senior (Level 1 of club football), 2 Intermediate (Level 2 of club football) from the Connacht region were recruited for this study. All 49 players were tested in the preseason period (July 2021) following lockdown, in which no field sports were permitted. A modified and condensed club season was run from August to November 2021 due to the Covid-19 pandemic.

Injury questionnaires, ethical approval and pre-screening was outlined as per Study 1 and 2.

Participants underwent an isometric assessment, eccentric assessment and then finally the isokinetic assessment to complete the strength battery (Table 6.1). Participants were asked to do no lower body resistance exercise or partake in any strenuous exercise 48hrs before testing. An identical warmup protocol was used for all players preceding the test; 10 minutes on cycle ergometer with low resistance followed by lower limb dynamic mobility (Bennell et al., 1998).

Table 6. 1: *Sequence of Strength Test Battery*

Time	Exercise
0 mins	Warm up on Cycle Ergometer
10mins	Movement and mobility routine (Dynamic stretching, Yoga Plex, Thoracic extensions, Sumo Squat)
13mins	ISO_{BI} Assessment
15mins	ISO_{UNI} Assessment
17mins	Passive Recovery – (Walk)
24mins	Self-selected dynamic exercise routine
30mins	Isokinetic Assessment

6.2.2 Isokinetic assessment

Participants were allowed to actively rest prior to the isokinetic assessment, the testing methodology was explained, and the participant was allowed to ask questions to ensure a full understanding of the process (Table 6.2). Subjects were informed that if pain arose during the test to tell the researcher immediately. They then performed a self-selected dynamic exercise routine for 2-3 mins and tests were performed on a Biodex-System II dynamometer (Biodex Medical, Shirley, New York).

Table 6. 2: Sequencing of Isokinetic assessment

Isokinetic Assessment
1. Explanation of methodology, subject strapped and stabilised, active alignment of dynamometer head in mid-range with centre of knee, patient details entered and maximum range of motion selected (Circa 120^0), gravity correction was performed with the knee limb in full extension.
2. 60^0/s concentric knee extensors and flexors (Isokinetic mode) – 3 submaximal repetitions followed by 20-30seconds of passive movement. Test begins in full flexion with 5 maximal repetitions followed by a rest period of 90 seconds. 180^0/s Concentric knee extensors and flexors– 3 submaximal repetitions followed by 20-30seconds of passive movement. Test begins in full flexion with 5 maximum repetitions. Process repeated on other limb and 90 secs recovery followed.
3. 60^0/s eccentric knee extensors and flexors (Passive Mode, 1 set of eccentric quadriceps followed after a recovery period of 1 set of eccentric hamstrings) – Dynamometer head aligned in midrange with active contraction of the quadriceps. Knee extensors eccentric contraction of 3 sub-maximal repetitions and 5 maximal repetitions. 90 second recovery period. Then alignment of the dynamometer head by active contraction of the hamstrings in mid-range. Knee flexors eccentric contraction of 3 sub-maximal repetitions and 5 maximal repetitions. The opposite limb was then tested.
4. 180^0/s eccentric knee extensors and flexors (Passive Mode) – Dynamometer head aligned in midrange with active contraction of the quadriceps. Knee extensors eccentric contraction of 3 sub-maximal repetitions and 5 maximal repetitions. 90 second recovery period and alignment of the dynamometer head by active contraction of the hamstrings in mid-range. Knee flexors eccentric contraction of 3 sub-maximal repetitions and 5 maximal repetitions. The opposite limb was then tested which completed the battery.

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The subject was sat upright in the seat of the dynamometer, and it was adjusted to ensure that the upper back and the upper limb was fully supported via the seat slider and seat height and both measurements were recorded. The subject was asked to hold a deep breath while fixing shoulders, pelvis, and thigh of tested leg using stabilisation straps (Bennell et al., 1998), with the seat belts located on either side of the subject. The back of the seat was adjusted so the subject's trunk angle was at 90^0, and the seat length adjusted to ensure the subject's thigh was fully supported with knee flexing freely. The limb lever was adjusted and recorded so the bottom of the lever was set just above the malleolus, and this position recorded. The dynamometer's axis of rotation was lined up with the axis of rotation of the subject's tested knee. The limb was positioned in mid-range, palpated at the medial and lateral joint line (lateral femoral condyle) and this point aligned with the axis of rotation. The ankle strap was then applied to lock the participant in position. Following this range of motion (ROM) was set for knee extension, the participant extended the knee to terminal end range. The participant was then instructed to pull back into flexion to end point and toward limit set. The knee has held in full extension with the hold button and the anatomical position calibrated, also with the subject relaxed the limb was weighed. The subject was instructed to hold the handgrips located on either side of the seat at all times. To familiarise themselves with the testing procedure each participant then performed 3 submaximal extensions and flexions at 60 ^{0}/s, following this they were allowed 20-30s of passive movement and recovery where they then initiated the test by pulling and holding the lever in full flexion. Verbal cues such as 'Kick out as hard and as fast as possible' for concentric quadricep, and 'Pull back as hard and as fast as possible' for concentric hamstring were used and five maximal repetitions performed. A rest period of 90secs was then undertaken and the same procedure was repeated for 180 ^{0}/s. On completion, sides were swapped, the other limb was setup and the dynamometer setup mirrored to repeat the process. Following completion of the concentric testing the dynamometer automatically changed over to passive mode prior to the eccentric testing of the quadriceps at 60 ^{0}/s. There was a recovery period of 90secs, during this period the limb was positioned in mid-range and the subject instructed to kick out for 5 secs, to ensure on active quadriceps contraction the axes remained aligned. If this was not the case the seat was lowered and then the process repeated until the axes remained aligned during active contraction of the quadriceps in midrange. It was made clear that the machine moved alone for eccentric actions. Once the recovery period was elapsed and the knee joint aligned with a "active quadriceps contraction" the participant undertook 3 submaximal eccentric extensions at 60 ^{0}/s with passive knee flexion at 60 ^{0}/s. They were then counted down from 3-2-1 and the eccentric test begun from terminal extension into flexion. Subjects were encouraged to 'push as hard as possible' during eccentric knee extension and completed 5 maximal repetitions. There is no preceding concentric contraction of the quadriceps which may reactivate the quadriceps and maximise force production, prior to eccentric testing. They were once again given 90 secs rest period prior to eccentric testing of the hamstrings at 60 ^{0}/s. During this period the limb was once again positioned in mid-range and the subject instructed to pull back for 5 secs, to ensure on active hamstrings contraction, the axes remained aligned. If this was not the case the seat height was increased and then the process repeated until the axes remained aligned during active contraction of the hamstrings. Once the recovery period was elapsed and the knee joint aligned with a "active hamstrings contraction" the participant undertook 3 submaximal eccentric flexions at 60 ^{0}/s with passive extension of the knee 60 ^{0}/s. They were then counted down from 3-2-1 and the eccentric test begun by pulling from flexion into terminal extension. Subjects were encouraged to 'pull as hard as possible' during eccentric knee flexion and completed 5 maximal repetitions. This process was again repeated for 180 ^{0}/s. Once this testing sequence had been completed the opposite side was tested and the protocol repeated by firstly mirroring the seat up of the dynamometer as per the tested limb and the contralateral limb tested again at speeds of 60 ^{0}/s and 180 ^{0}/s. The following calculations were then obtained from the results:

1) Peak torque (Nm), obtained at 60^{0}/s (PT60); 180^{0}/s (PT180); peak torque normalised to body mass (Nm.kg^{-1}) at 60 ^{0}/s (PT60%) and 180 ^{0}/s (PT180%) for both concentric and eccentric contractions.
2) Conventional ratio, concentric peak torque of hamstring muscles divided by peak torque of the quadriceps muscles at 60 ^{0}/s (Hcon : Qcon$_{60}$) and 180 ^{0}/s (Hcon : Qcon$_{180}$) (Yeung *et al.* 2009).
3) Hamstring to opposite hamstring ratio in concentric mode at 60 ^{0}/s (Hcon : Hcon$_{60}$) and 180 ^{0}/s (Hcon : Hcon$_{180}$).
4) Functional ratio, eccentric hamstring peak torque versus concentric quadriceps peak torque at 60 ^{0}/s (fHe:Qc$_{60}$) and 180 ^{0}/s (fHe:Qc$_{180}$) (Yeung et al., 2009).

Even though eccentric knee extension is not required for any of the above ratios it was included as it may be useful in investigating more dynamic control ratios (not included in our objectives). IKD data is considered controversial due to the lack of experimental control (as previously discussed in Chapter 2) (Bennell et al., 1998, Zvijac et al., 2013, van Dyk et al., 2016). When calibration, gravity correction, and patient positioning are all standardised reliability increases (>0.8) (Feiring et al., 1990, Pincivero et al., 1997, McCleary and Andersen, 1992). As a result, the methodology in which the centre of axis is aligned (under isometric contraction) and the passive mode of testing, indicate a strong correlation in test-retest for peak torque of the quadriceps and hamstrings in both eccentric and concentric modes. This is consistent with other studies in which values of 0.8-0.9 have been reported which indicate good reliability values consistent with previous IKD methodologies (Impellizzeri et al., 2008).

6.2.3 Eccentric strength assessment

As per studies 1 & 2.

6.2.3 Bilateral Isometric strength assessment

As per study 2.

6.2.4 Unilateral strength assessment

As per study 3.

6.2.5 Test-Retest protocol

Four recreational athletes (23+/-3yrs) were tested on two occasions within 3-7 days of initial testing. Participants were asked to do no lower body resistance exercise or partake in any strenuous exercise 48hrs before testing or complete any strenuous exercise between the tests. All participants completed a pre-test questionnaire to include physical characteristics such as height and weight, and if there were any previous lower limb musculoskeletal injuries. An identical warmup protocol was used for all players preceding the test; 10 minutes on cycle ergometer with low resistance followed by lower limb dynamic stretching and the protocol implemented as previously outlined.

6.2.6 HSI reporting

All retrospective HSI injuries are reported from hereon. Prospective HSI injuries were also recorded throughout the 3 months of the truncated season and due to the low incidence of injury (low statistical value) have not been widely reported in this study.

6.2.7 Data analysis

Data were analysed using SPSS software package V.18.0 (SPSS Inc, Chicago, Illinois, USA). Descriptive statistics for all measures were determined using a Shapiro-Wilk test in SPSS. An Interclass correlation coefficient test was performed to determine reliability of the Isometric strength testing. Reliability was assessed according to quantitative guidelines for intraclass correlations, with an ICC of less than 0.79 regarded as poor, 0.80-0.89 as moderate and above 0.90 as high (Vincent, 2005). An ICC less than 10% was set as a level of reliability (Cormack et al., 2008, Opar et al., 2013a).

Normal distribution was confirmed using the Shapiro-Wilk test. Owing to the unequal group sizes, the Mann-Whitney U test was used in pre-season to assess the differences between the injured and the uninjured groups for maximal force, maximal torque. In the injured group an independent T-test was used to compare involved to non-involved limb. Cohen's $d \pm 90\%$ confidence intervals (90% CI) were calculated to determine for effect sizes (Hopkins 2006). Differences were considered as trivial (<0.2), small (≥0.2), moderate (≥0.5), or large (≥0.8) (Batterham and Hopkins, 2006).

Correlation between test-retest was performed using Spearman rank order correlation statistics. Strength of relationships was determined a priori as weak (r=0.1-0.29), moderate (r=0.3-0.49), or strong (r=*0.*5-1.0) (Ramsey, 1989). Usually 10 pairs of data are required for Spearman's, so this should be borne in mind when interpreting this methodology.

6.3 Results

6.3.1 Participant and injury details

A total of 49 participants (26.5+/-2.4yrs; 81.6+/-9.1 kgs) 20 of whom sustained a previous hamstring strain in the past 12 months with mean time lost per HSI to training or matches 20.1±7.1 days. The major mechanism was high-speed running and kicking, accounting for 89% and 11% of hamstring strains, respectively. 6 players sustained a HSI during the playing season.

6.3.2 Test-Retest

Test-retest correlations for peak torque in both eccentric and concentric modes of testing were $r^a = 0.84$ to $r^a = 0.94$ (Table 6.1 & Table 6.2).

Table 6. 3: *Test-retest correlation for concentric peak torque (Nm).*
You will see this ranges between 0.94-0.97 for 60-180^0/s.

Extension 60 ^{0}/s		**Flexion 60 ^{0}/s**		**Extension 180 ^{0}/s**		**Flexion 180 ^{0}/s**	
Test 1	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
183+/-43 Nm	179+/-38 Nm	183+/-43 Nm	179+/-38 Nm	151+/-7 Nm	139+/-4 Nm	86+/-7 Nm	81+/-8 Nm
r = 0.95		r = 0.97		r = 0.94		r = 0.95	

Table 6. 4: *Test-retest correlation for eccentric peak torque (Nm)*
You will see this ranges between 0.85-0.92 for 60-180^0/s.

Extension 60 ^{0}/s		**Flexion 60 ^{0}/s**		**Extension 180 ^{0}/s**		**Flexion 180 ^{0}/s**	
Test 1	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
222+/-72 Nm	228+/-83 Nm	116+/-42 Nm	118+/-32 Nm	233+/-67 Nm	217+/-78 Nm	120+/-40 Nm	117+/-38 Nm
r = 0.85		r = 0.92		r = 0.94		r = 0.88	

6.3.3 Previous HSI Isometrics and Eccentric strength

There were no differences reported for Iso$_{BI}$ and NB$_{Ecc}$ strength between the involved and un-involved sides and also between the injured and non-injured groups ($p<0.05$). In Iso$_{UNI}$ there were significant differences between the injured and non-injured group for absolute force, relative force, scaled force, absolute torque, scaled torque and relative torque measures (p>0.05).

Table 6. 5: Comparison of Iso$_{UNI}$ variables from players with previous hamstring injury (injured limb) versus non-injured players
(Mean of L+R, there were no difference between dominant and non-dominant limbs therefore limbs were grouped).
You will see significant differences for all metrics for non-injured players with effect sizes from 0.8-1.0.

	Previous HSI (n=20)	**Non-injured (n=29)**	**ES**
Force (N)	363±62	417±72**	0.80
Relative force (N.kg^{-1})	4.48±0.85	5.19±0.86**	0.92
Scaled force (N)	6.68±1.26	7.75±1.28**	0.92
Torque (Nm)	156±28	185±34**	0.93
Relative Torque (Nm.kg^{-1})	1.92±0.38	2.33±0.39**	1.06
Scaled Torque (Nm)	1.88±0.37	2.28±0.38**	1.06

*Significant difference P>0.05, ** Significant difference P>0.01

There no significant differences between players with and without previous HSI (injured limb) versus the non-involved limb for both NB$_{ECC}$ and ISO$_{BI}$ (Table 6.6).

Table 6. 6: *Comparison of NB$_{ECC}$ and ISO$_{BI}$ from players with previous HSI and non-injured group.*

	Previously injured group				**Non-injured group**			
	NB$_{ECC}$		**ISO$_{BI}$**		**NB$_{ECC}$**		**ISO$_{BI}$**	
	Injured limb	**Non-involved**	**Injured limb**	**Non-involved**	**Dominant**	**Non dominant**	**Dominant**	**Non dominant**
Ab Force (N)	236±55	237±52	228±51	227±48	243±73	245±66	221±65	216±68
Relative force (N.kg^{-1})	2.91±0.71	2.91±0.65	2.83±0.71	2.82±0.68	3.0±0.85	3.05±0.82	2.76±0.82	2.71±0.89
Absolute Torque (Nm)	101±23	101±22	98±23	98±22	108±33	109±30	98±29	96±31
Relative Torque (Nm.kg^{-1})	1.24±0.30	1.24±0.27	1.23±0.33	1.21±0.30	1.33±0.38	1.35±0.37	1.24±0.41	1.20±0.39

6.3.4 Previous HSI Isokinetic concentric and eccentric (passive mode) torques

The injured limb have significantly weaker strength when comparing the injured limb to the non-inured group for eccentric knee extensors, in both concentric and eccentric knee flexors at 60^0/s. The non-injured group have significantly weaker concentric knee extensor strength when comparing the injured group involved side to the non-inured group at 180^0/s.

Table 6. 7: *Comparing concentric and eccentric hamstring variables from players with previous hamstring injury (injured limb) and the non-injured group.*

(Mean of L+R, there were no difference between dominant and non-dominant limbs therefore limbs were grouped).

You will observe that 5 torque metrics at 60 ^{0}/s and 2 at 180^0/s were significantly lower in the injured group.

	60 ^{0}/s			180^0/s		
	Injured limb	**Non-injured Group**	**ES**	**Injured limb**	**Non-injured group**	**ES**
PT$_{con}$ extension	190±48	204±28	0.36	182±51	152±21**	0.77
PT$_{ecc}$ extension	164±44	253±57**	1.74	230±67	231±61	0.02
PT$_{ecc}$ flexion	88±31	130±28**	1.42	126±23	127±27	0.04
PT%$_{con}$ extension	2.32±0.58	2.54±0.36	0.46	2.23±0.61	1.88±0.19*	0.77
PT%$_{con}$ flexion	1.11±0.27	1.24±0.22*	0.52	1.09±0.27	1.01±0.20	0.33
PT%$_{ecc}$ extension	2.0±0.56	3.17±0.78**	1.8	2.82±0.83	2.89±0.82	0.08
PT%$_{ecc}$ flexion	1.08±0.39	1.62±0.32**	1.51	1.54±0.30	1.60±0.35	0.18

*Significant difference P>0.05, ** Significant difference P>0.01

In the injured group the opposite to opposite hamstring ratios (injured v non-injured) were 0.92+/-0.14 and 0.94+/- 0.15 for Hcon : Hcon$_{60}$ and Hcon : Hcon$_{180,}$ respectively. There was a significant difference in fHe : Qc$_{60}$ and fH:Qc$_{180}$ when comparing the involved limb to the non-dominant side in the un-injured group (Table 6.8).

Table 6. 8: *Comparison of functional ratios from players with previous hamstring injury (injured limb) versus non-dominant side of un-injured group*

fHe : Qc$_{60}$			**fHe : Qc$_{180}$**		
Injured limb	**Non Dominant**	**ES**	**Injured limb**	**Non Dominant**	**ES**
0.48±0.18	0.65±0.16**	1.0	0.74±0.25	0.85±0.20*	1.0

*Significant difference P>0.05, ** Significant difference P>0.01

There was a significant difference in both fHe: Qc_{60} and fHe: Qc_{180} and also in Hcon : $Qcon_{180}$ when comparing the injured group to the dominant side of the non-injured group.

Table 6. 9: *Comparison of conventional and functional ratios from players with previously hamstring injury (injured limb) versus non-previously injured group*

	60 ^{0}/s		ES	180 ^{0}/s		ES
	Injured limb	**Dominant**		**Injured limb**	**Dominant**	
Hcon : Qcon	0.50±0.15	0.51±0.10	0.08	0.51±0.15	0.55±0.10*	0.31
fHe:Qc	0.48±0.18	0.65±0.16**	1.0	0.74±0.25	0.85±0.19*	0.5

*Significant difference P>0.05, ** Significant difference P>0.01

Of the 49 participants 7 (5 dominant) sustained a HSI during the playing season, of which 5 re-occurred with a mean time lost per HSI to training or matches of 16.4±12 days. Three occurred during training and 2 in matches while high-speed running. There were no differences noted in the injured group for Iso_{UNI}, Iso_{BI}, Ecc strength in the involved and un-involved sides and also when comparing to the non-injured group ($p<0.05$). There were also no differences noted in the injured group for any isokinetic strength variables in the involved and un-involved sides and also when comparing to the non-injured group ($p<0.05$).

6.4 Discussion

The findings from our study indicate 1) Good reliability (r = 0.8-0.9) of the IKD methodology 2) players with previous HSI are significantly weaker in Iso_{UNI} strength in comparison to players without HSI (Table 6.5) 3) relative to body weight previously injured players (limbs) have lower concentric and eccentric hamstring torque at 60 ^{0}/s in comparison to non-injured group, significantly lower ratios in the injured limb for Hcon:$Qcon_{180}$ (Table 6.9) and FHe_{60}:Qc_{60} and FHe_{180}:Qc_{180} when comparing to the dominant/non-dominant limbs of the non-injured group (Table 6.8) 4) no differences for any of the prospective data.

The injured players in this study were significantly weaker in Iso_{UNI} strength but exhibited no differences in Iso_{BI} and NB_{Ecc} strength. This further corroborates the trend towards a lack of sensitivity in NB_{ECC} strength to detect residual differences in injured players from Studies 1 & 2. Iso_{BI} were not significantly different in this current study cohort whereas we have previously reported residual weakness during preseason (study 2). One of the limitations of testing bilaterally is that it may allow for neural crossover. Iso_{UNI} test however, test each limb individually and thus potentially isolates any muscular weaknesses. Also, in Iso_{UNI} the opposite hip is placed into extension and subjective feedback from participants indicated that this placed a counter stretch on the limb being tested prior to MVIC. Iso_{UNI} assesses muscle function in a long lever 150^0 position, NB_{Ecc} breakpoint occurs at 103^0-126^0 and it can be debated that Iso_{UNI} may be more sensitive to underlying residual deficits as this long lever position may more closely simulate the mechanism of injury seen in late swing phase/early stance in which the contralateral limb is also in extension (Chumanov et al., 2012).

Players with previous HSI are weaker both concentrically and eccentrically at 60 ^{0}/s in comparison to non-injured peers (Relative to BW and absolute torque). Previously a testing velocity of 60 ^{0}/s for IKD assessment has been recommended as higher speeds decrease the velocity arc (the portion of the movement in which the dynamometer reaches true testing speed, constant velocity) and may also help explain why these differences are not as prominent in the current study at 180 ^{0}/s. This is evident even though 60 ^{0}/s is not close to the physiological joint angular velocities of kicking and high speed running (730 ^{0}/s and 860-1720 ^{0}/s) (Nagahara et al., 2014, Nunome et al., 2002). Strength at 30 °/s and 120 ^{0}/s for previously injured athletes has moderate evidence whereas high velocity measures of 240^0/s and 300^0/s have very limited evidence (Maniar et al., 2016) and concurs with the trends within the current study. Lower levels of eccentric knee flexor strength elevate the risk of future HSI (Bourne et al., 2017) while lower hamstring strength at 30 ^{0}/s and 120 ^{0}/s is associated with increased HSI risk in soccer players (Fousekis et al., 2011). Furthermore, during pre-season reduced hamstring eccentric peak torque's at 30^0/s <2.44 times body weight is associated with 5.6-fold increase in the risk of HSI in professional footballers (Lee et al., 2018).

Hamstring-to-opposite hamstring at both 60^{0}/s (0.92±0.14) and 180^{0}/s (0.94±0.15) in the injured group are similar to the 0.9 cut off as proposed by (Orchard et al., 1997). Soccer players who have isokinetically derived strength imbalances and are fivefold more likely to sustain severe injuries (>30 days lost) compared to those without imbalances (Croisier et al., 2008). The correction of these isokinetic parameters through strength training can reduce the risk of HSI to the same level as those players without imbalances (Croisier et al., 2008).

Conventional ratio's in the injured limb at 180 ^{0}/s are lower in comparison to the dominant limb of un-injured players. Values here, of 0.5-0.51 for $Hcon:Qcon_{60}$ may indicate that even un-injured players are at risk of HSI as this ratio can be utilized to discriminate risk in preseason, <0.50 increases the risk of hamstring injury 3 fold in professional soccer players and in Brazilian professional soccer players, outside of 0.55-0.65 by 8-45 fold (Lee and Kim, 2017, Liporaci et al., 2019). Previously injured club footballers here report significantly lower ratios with a small effect size for $Hcon:Qcon_{180}$, when comparing to the un-injured dominant limb and lower than those values recommended for preventative purposes, as <0.6 significantly increased the risk of hamstring injury by 17 times (Yeung et al., 2014).

Underlying weakness existed even more so in functional ratios with the injured group having significantly lower $fHe:Qc_{60}$, $fHe:Qc_{180}$ when comparing to both the non-dominant and dominant limb of their uninjured peers. This concurs with the findings in professional soccer players where the $fHe:Qc_{60}$ is significantly different in injured (0.65+/-0.21) v non injured players (0.8+/-0.15) (Dauty et al., 2003). However values in the injured limb (0.48 and 0.74) are somewhat lower in comparison to reported values in the literature of 0.79+/- 0.19 and 0.96 +/- 0.19 for 60 ^{0}/s and 180 ^{0}/s, respectively (Baroni et al., 2020). It is specific in determining the ability of the eccentrically acting hamstring to brake the action of the concentrically contracting quadriceps during the late swing phase of the gait cycle (Yeung et al., 2009). Lower ratios may represent the inability of the hamstrings to support joint movements performed by the quadriceps as the hamstrings become an antagonist (Aagaard et al., 1998), and one would deduce therefore that the hamstrings would be susceptible to injury as a result of exposure to high speed running. Ratios of $Hcon:Qcon_{180}$ and $FHe_{60}:Qc_{60}$ and $FHe_{180} : Qc_{180}$ are significantly lower in the injured limb and when comparing to the dominant limb of the non-injured group. Eccentric strength is significantly greater in the preferred kicking leg (Ruas et al., 2015) and this reliance on the dominant side may help explain the fact that in Australian rules football 38-71% of injuries have occurred on the dominant or kicking side (Bennell et al., 1998, Cameron et al., 2003, O'Sullivan et al., 2008).

Eccentric hamstring torque decreases during match-play as a function of time (Greig and Siegler, 2009) and coupled with the extra stress and fatigue with kicking in the dominant limb could possibly make the kicking limb more susceptible to fatigue and increase HSI during match play and is a factor to consider given the kicking nature of the sport. Limb dominance is also preferred for voluntary motor acts in humans (Carpes et al., 2010), preference and task complexity (Carpes et al., 2010).

IKD testing and NB_{Ecc} strength has also been previously studied. A large study of 413 soccer players who had a history of HSI in the past season had also no differences in NB_{Ecc} variables (van Dyk et al., 2018). They did however also have no differences in relation to their IKD variables. The NB_{Ecc} methodology is similar, however the IKD methodologies are different mainly around the alignment of the centre of axis and testing eccentrically in passive mode. Position of testing and differences in joint angles as a result may help explain this difference between the studies (Jakobi and Chilibeck, 2001, Sale, 2008). IKD seems to be more sensitive in discerning differences and it may be reasonable the novel methodology to be the main factor, also given the fact that a high reliability is reported ($r = 0.8$-0.9). Eccentric isokinetic knee function has been shown to occur following specific HSI intervention programs (Mjølsnes et al., 2004, Timmins et al., 2015, Guex et al., 2016) with a 2.3-8 degrees shift in the angle of peak knee flexor torque towards longer muscle lengths (Brockett et al., 2001, Clark et al., 2005, Seymore et al., 2017, Brughelli et al., 2010). This increases the ability of the hamstrings to generate high levels of torque at longer muscle lengths (Bourne et al., 2017) due to altered hamstring activation (Bourne et al., 2015), architecture (Timmins et al., 2015, Timmins et al., 2017) and morphology (Silder et al., 2008). This shift in torques towards more longer optimums is associated with a decreased risk in HSI (Brockett et al., 2004, Brughelli and Cronin, 2008) and given the underlying weakness in Iso_{UNI} and that the eccentric angle of peak torque occurs at significantly shorter muscle lengths in previously injured Gaelic footballers (Mackey et al., 2011) the mode of testing should also be biased towards the ability to detect weaknesses at longer muscle lengths. This may also explain the eccentric and isometric deficits reported here.

Prospectively, there no differences in any of the strength parameters in players which experienced HSI, unfortunately the lack of HSI due to the condensed club season was run from July through to September impacted the analysis. However, running this current battery throughout a full playing season may help provide useful information for the risk of future HSI. Interestingly, five of the players out of twenty who became injured had suffered previous HSI and would further corroborate the evidence in relation to previous injury being a prevalent high-risk factor within the sport. As mentioned previously this was too low a injury incidence to examine with any great deal of effect sizes. While the data was anlaysed statically no differences were noted and hence not reported here as a result of having little significance from a research perspective.

Therefore the hypotheses proposed in which:

- The reliability of a novel IKD methodology is unsupported and requires more research.
- ISO_{BI}, ISO_{UNI}, NB_{ECC} strength is lower in the involved limb of players with HSI and injured players are weaker compared to their uninjured counterparts is rejected.
- IKD concentric and eccentric peak torque is lower in involved limb of players with HSI and players are weaker compared to their uninjured counterparts is supported.
- IKD ratios are lower in the involved limb in players with HSI and lower in the injured group compared to the uninjured group is supported.

6.5 Summary

Reliability of a novel IKD methodology requires more research due to the size of the study where assessment at 60 ^{0}/s for concentric and eccentric torque is more sensitive to previous HSI and also Hcon : $Qcon_{180}$ and FHe_{60}:Qc_{60} and FHe_{180}:Qc_{180} (but only in comparing to the dominant limb of a un-injured player). The trend for isometric testing to discern for previous HSI continued, particularly so, for Iso_{UNI} strength. Once again as noted in previous chapters NB_{ECC} strength assessment seems to have limited value for HSI. The main advantage of the novel isometric tests is that they 1) test in a long lever position similar to that of late swing early stance 2) and now also test unilaterally with the contralateral hip in 20^0 of extension.

6.6 Limitations

- Undertaking a strength battery involving 4 maximal tests is time consuming and possibly fatiguing on the athlete and challenging to ensure maximal peak torque values consistently are produced through all modes of testing. It may be worthwhile to consider isolating each mode of testing with an individual day for each test. This however places challenges around access to players, time of day and previous activity level.
- The IKD methodology is required to be undertaken by an experienced IKD or Biodex operator as it involves Isokinetic and Passive modes and changing over the dynamometer head and re-aligning as per the protocol, as outlined. The sequencing of this (Table 6.2) requires practise to ensure reproducibility and repeatability levels are high as per the reliability work undertaken before the main study. Again, it may be worthwhile to consider alternative days in which isokinetic and passive modes can be isolated.
- In future it would be useful and worthwhile to look at specific angles of peak torque (for IKD, NB_{ECC}, ISO_{UNI}, ISO_{BI}) which would be useful in comparing angles for all three modes of testing and to ascertain where this occurred (short or long lever).
- The recommendation is to test at 60^0/s and assess both concentric and eccentric knee flexor and extensor strength at this velocity rather than include a large battery of test speeds which have the potential to fatigue the athlete.

STUDY 5

Fascicle Length and Pennation Angle in the Dominant Limb of Gaelic Footballers, Comparison to Players with previous HSI and its relationship to Isometric and Eccentric Strength.

7.1 Introduction

Nordbord assessment (nordic hamstring exercise) does not differentiate GF players in pre-season who became injured later in the season, while it also does not detect residual weakness following injury even though isometric strength deficits are present (Study 1 & 2). Iso_{BI} is as a reasonable indicator of previous HSI (Study 1) and Iso_{UNI} strength is significantly weaker in players with previous HSI, the specificity of the Iso_{UNI} methodology the contributory factor (Study 4). Shorter Lf has been identified in players with previous HSI and peak eccentric force has been associated with 27% of the variance in BFlh Lf in professional rugby players (McGrath et al., 2019). The association of isometric and eccentric knee flexor strength to Lf in the aetiology of a HSI in Gaelic footballers has b not been previously investigated and such information would be useful given the high level of HSI and recurrence within the sport. The majority of studies within the literature use methodologies which estimate L_f which in turn either underestimates or overestimates L_f. EFOV is proposed to measure BFlh Lf rather than estimating Lf, thereby providing useful and novel information as to whether BFlh architecture can be considered a risk factor regarding HSI in elite Gaelic football.

The aim of this study was to investigate the architecture of the BFlh in Gaelic footballers and assess the relationship between L_f, θ_p and NB_{Ecc}, Iso_{BI}, Iso_{UNI} strength. The objective was to determine whether 1) there was a difference in BFlh Lf between injured and uninjured players with previous HSI 2) there was a difference in θ_p between injured and uninjured players with previous HSI 3) there was a relationship between L_f, θ_p and NB_{Ecc}, Iso_{BI}, Iso_{UNI} strength in players with previous HSI.

7.1.1 Hypotheses

- BFlh Lf is shorter in players with previous HSI
- θ_p is greater in players with previous HSI
- L_f, θ_p has a strong association with NB_{Ecc}, Iso_{BI}, Iso_{UNI} strength in players with previous HSI.

Note:
To clarify and for complete transparency this study was undertaken in line with the cohort from Study 3 testing in July 2020. As in study 3 this was initially designed as both a retrospective and prospective study. There were only 4 ultrasound scans (with sufficient image quality) from injured players (n=6) during the season therefore, prospective data is not anlaysed or presented.

7.2 Methods

7.2.1 Participants and study design

As per study 3. Players underwent BFlh assessment prior to testing in Study 3. Sixteen ultrasound scans of players with previous HSI (n=16) were analysed and compared to 24 images of a non-injured cohort (n=24).

7.2.2 HSI reporting

As per study 3.

7.2.3 Biceps Femoris Long Head Muscle Architecture Assessment

Fascicle length and pennation angle of the BFlh of the previously injured limb was determined from ultrasound images taken along the longitudinal axis of the muscle belly using a 7 cm transducer (GE Logic Healthcare, Wauwatosa, USA) with an imaging depth of 8 cm. All scans were performed with participants in the prone position, the knee joint fully extended and the hip neutral following at least 5 minutes of inactivity. The muscle was palpated to determine origins and insertion of the BFlh and the scanning site was determined between the inferomedial impression of the ischial tuberosity and the lateral aspect of the head of the fibula. Ultrasound gel was applied along the line of the BFlh. The ultrasound probe was applied longitudinally and perpendicular to the posterior thigh with minimal pressure of the probe on the skin due to its influence on the accuracy of measurements (Klimstra et al., 2007). To setup the ultrasound unit, depth was set to (8), Zoom button to (6-8), drop frequency to 8 and the proximal and distal segments scanned, identified and marked (Figure 7.1).

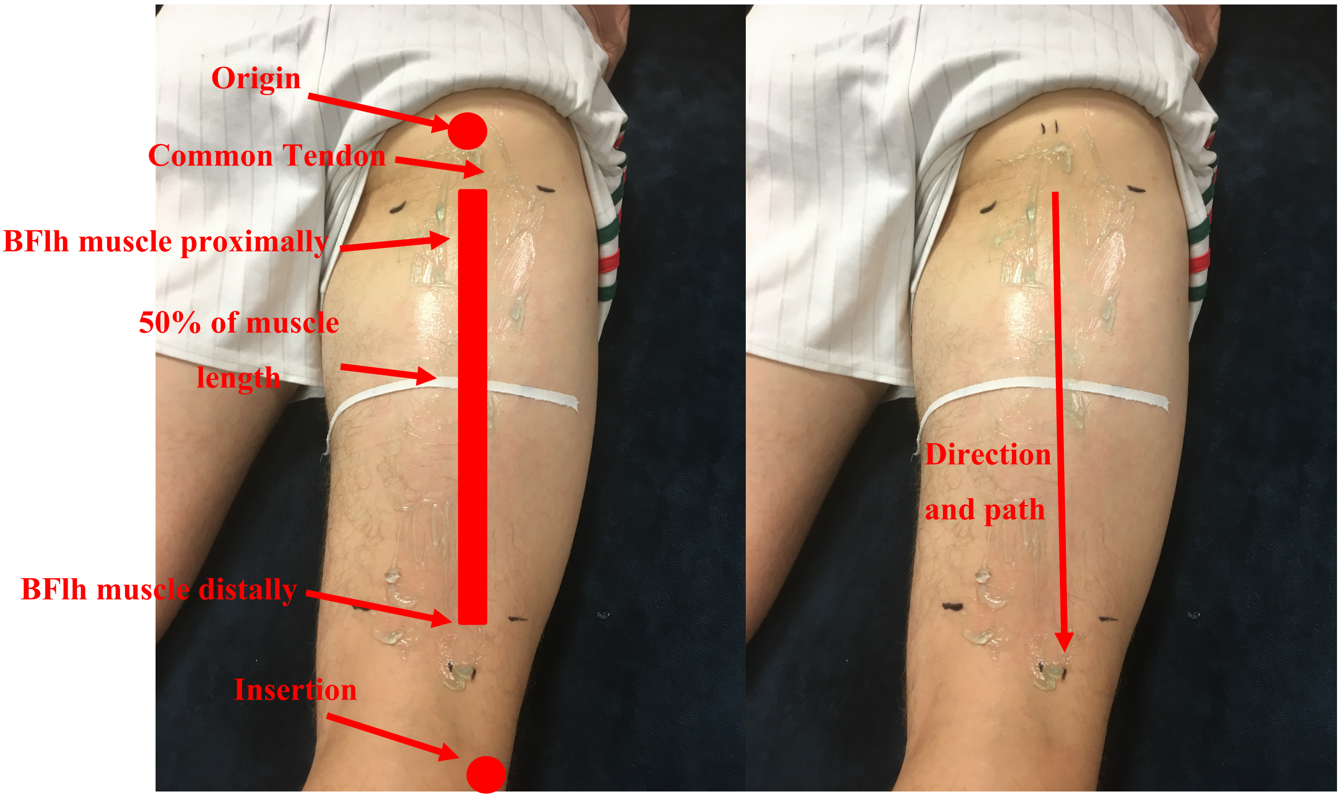


Figure 7. 1: *Details of BFlh Anatomy and surface preparation for ultrasound scan.*

The proximal portion was located first with the ultrasound transducer aligned to the fascicle plane, after which it was slowly moved along this plane from the proximal to distal portion and the probe was orientated so that the fascicles remained continuous and the aponeuroses remained parallel and then disappeared from view. The point at which the BFlh becomes intramuscular, in which the proximal aponeuroses began to become more flat and superficial (Battermann et al., 2011) with some fibres evident on the lateral aspect (Woodley and Mercer, 2005b) was marked as the origin. The insertion of the BFlh was identified by slowly following the aponeuroses distally and laterally along the mid belly of the BFlh where both the superficial and intramuscular aponeuroses were kept parallel on screen by slightly manipulating the transducer to do so. Once it became apparent that only a superficial aponeurosis was evident with some distal muscle fascicles apparent on the lateral aspect of the knee was marked as the distal insertion. The medial and lateral boundaries were identified to identify the mid sagittal plane and this plane parked on the skin surface from origin to distal insertion points. The skin was cleaned free from acoustic gel and was marked longitudinally between these two points to identify the BFlh. Muscle length was measured with a tape measure on the skin surface and the mid-point measured and marked. A 5 mm wide strip of surgical tape (3M) was then placed transversely (so this midpoint was evident on the ultrasound images) on the skin surface to mark the centre point of muscle length. Transmission gel was then reapplied to the full length of the hamstring.

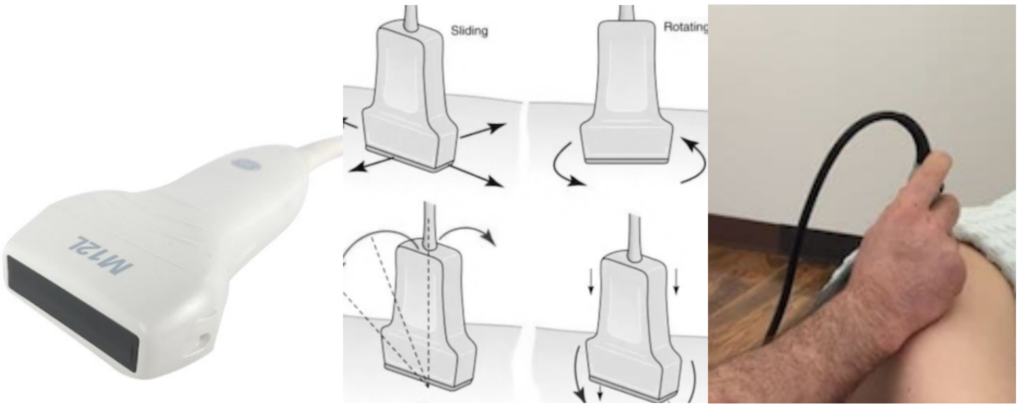


Figure 7. 2: *Transducer and its orientation when undertaking a proximal to distal scan* – to the left is the transducer with the contact area which was orientated to ensure aponeuroses remained parallel, middle image details the movements of the transducer to ensure this occurred, image to the right details the hand/transducer position when beginning at the proximal region.

The EFOV scan was performed on the injured limb of players with previous injury and on the dominant limb of the un-injured cohort. This began at the proximal marking for the origin previously identified as the conjoint tendon (see chapter 2). For each subject three full muscle scans were performed to ensure a quality image was attained for each subject.

Following the scan was performed by first setting the device depth to 7 cm, the Zoom button to (6-8) drop frequency to 8. The transducer was placed at approximately 25%-75% of muscle length. The scan was undertaken as described above and three scans performed for each participant.

Scan quality was checked for inclusion in the analyses. For this, in each of the participant's scans, two fascicles had to be traceable whereby the intermediate and superficial aponeurosis was evident and the path of fascicle clearly identified. L_f and θ_p were measured using a freely available image processing program (Image J 1.48v, National Institute of Health, Bethesda, USA). Both a proximal and distal fascicle were identified which passed through 50% of the total muscle length. A segmented line was then used to mark the proximal fascicle from the intermediate to superficial aponeurosis, taking into account fascicle curvature. Fascicle pennation angle was then measured between the drawn fascicle by overlaying it with the angle segment and then using the measure function to determine the angle. Following on from this, a second more distal fascicle was identified, and the process repeated above for both L_f and θ_p. Two scans were quality reviewed and analysed by a experienced researcher (as per the data analysis, below) to ensure L_f and θ_p were measured correctly.

7.2.4 Data analysis

The average of two fascicle lengths (proximal and distal) and their corresponding pennation angles were recorded from two separate longitudinal images, and the average of both images were used for analysis.

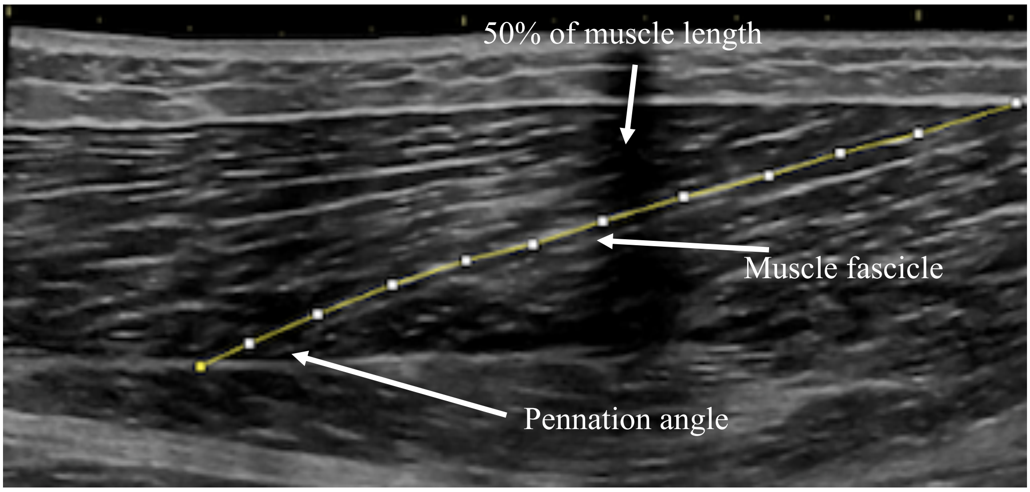


Figure 7. 3: Muscle fascicle and pennation angle.

Data were analysed using SPSS software package V26.0 (SPSS Inc, Chicago, Illinois, USA). Normal distribution of data was confirmed using the Shapiro-Wilk test. Owing to the unequal group sizes, the Mann-Whitney U test was used in pre-season to assess the differences between the injured and the uninjured groups for BFlh and pennation angle. Cohen's *d* ± 90% confidence intervals (90% CI) were calculated to determine for effect sizes (Hopkins 2006). Differences were considered as trivial (<0.2), small (≥0.2), moderate (≥0.5), or large (≥0.8) (Batterham & Hopkins, 2006).

Correlation between fascicle length and knee flexor strength was performed using Spearman rank order correlation statistics. Strength of relationships was determined a priori as weak (*r* = 0.1 - 0.29), moderate (*r* = *0*.3 - 0.49), or strong (*r* = 0.5 - 1.0).

7.3 Results

7.3.1 Participant and injury details

In total, 49 participants completed the muscle architecture assessments; however, only 40 of these were included in the study due to image quality issues with the scans of 9 participants. In total, 32 participants were right-sided and 8 were left-sided. There were 16 participants with previous hamstring injury, and 50% of these were on the dominant side.

7.3.2 Retrospective Fascicle length and Pennation angle

There was no significant difference in BFlh fascicle length and pennation between previously injured players (injured limb) and un-injured players (dominant limb). There was a moderate effect size identified for fascicle length (p>0.05, d=0.5) and a moderate correlation between BFlh fascicle length and pennation (Table 7.2)

Table 7. 1: *Biceps femoris long head (BFlh) fascicle length and pennation angle in previously injured and non- injured Gaelic football players*

	Previously Injured Players (Injured limb n=16)	**Non-injured Players (Dominant limb n = 24)**	**ES**	**P-value**
Fascicle length (cm)	8.8 ± 1.9	9.7 ± 1.8	0.5	P=0.241
Fascicle pennation angle (^{0})	22 ± 13	19 ± 4	0.3	P=0.392

Table 7. 2: *Correlation Biceps femoris long head (BFlh) fascicle length and pennation angle in the non-injured group (n=24)*

	Grade r^a	P
Pennation	0.526	<0.08

There were moderate correlations reported for fascicle length in the injured limb of previously injured players for ISO_{BI}, ISO_{UNI} (Table 7.3)

Table 7. 3: *Correlation Biceps femoris long head (BFlh) fascicle length with pennation angle and knee flexor strength in the injured group*

You will see fascicle length in the injured group was moderately correlated with θp ($r=0.377$, $P< 0.150$), Iso_{BI} ($r=0.442$, $P< 0.086$), Iso_{UNI} ($r=0.389$, $P< 0.136$) and weakly correlated with NB_{Ecc} ($r=0.144$, $P< 0.673$).

	Grade r^a	P
Pennation angle	0.377	<0.150
ISO_{BI} ($Nm.kg^{-1}$)	0.442	<0.086
ISO_{UNI} ($Nm.kg^{-1}$)	0.389	<0.136
NB_{ECC} ($Nm.kg^{-1}$)	0.114	<0.673

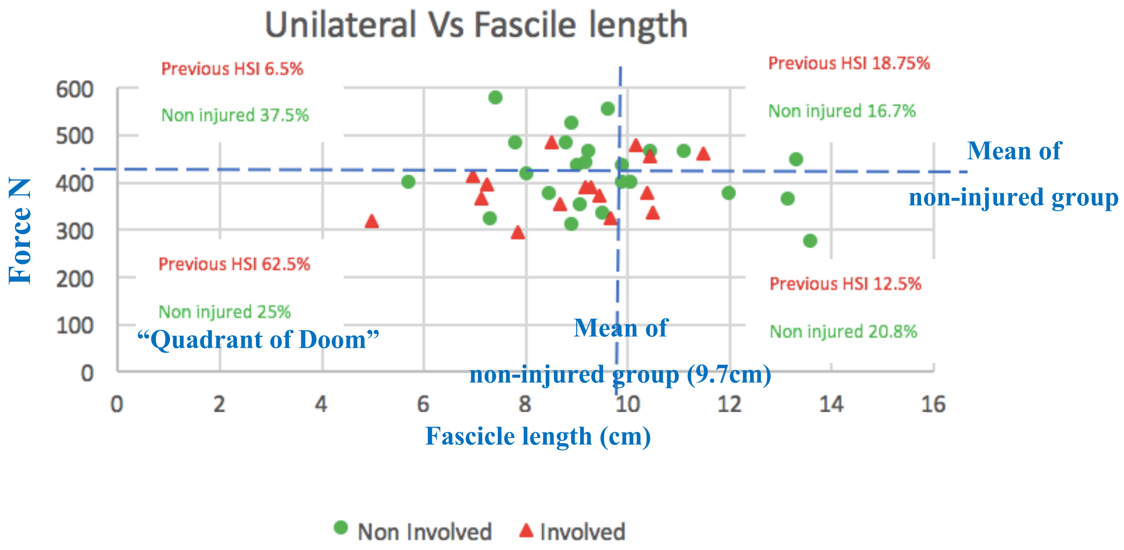


Figure 7. 4: *Fascicle length (cm) and unilateral isometric strength (N).*
You will notice greatest number of players with previous HSI (injured limb) (62.5%) in bottom left quadrant. You will see 62.5% of all previous hamstring injuries scored below the averages of the group for both fascicle length (9.9cm) and unilateral isometric strength (420N).

7.4 Discussion

The purpose of this study was to determine the L_f and θ_p of the dominant limb in club Gaelic footballers in relation to retrospective HSI. The findings indicate that BFlh L_f and θ_p do not differ between previously (HSI) injured and non-injured Gaelic footballers. In those players with previous HSI L_f and isometric strength is strongly related whereas NB_{Ecc} and L_f is not.

BFlh L_f is not significantly shorter however L_f in previously injured limbs are 10% shorter than their non-injured peers. θ_p is not statistically different in those players with previous HSI. It has been reported previously and widely acknowledged that football players, who have experienced HSI in the previous season have shorter fascicles than their non-injured counterparts (de Lima-E-Silva et al., 2020). Between-limb strength asymmetry in athletes with history of unilateral HSI within the last 18 months are also evident (Croisier et al., 2002, Opar et al., 2013c, Timmins et al., 2015, Timmins et al., 2017). Limbs without a history of HSI remain unchanged throughout the season (10.92 ± 0.76 cm vs. 10.62 ± 0.71 cm), whereas those having previous HSI injury end the season with shorter L_f than they begin with in both the un-injured (10.19 ± 0.92 cm vs. 9.53 ± 1.2 cm) and injured limb (10.18 ± 0.79 cm)

(Timmins et al., 2017). This suggests that athletes with HSI in the prior season have BFlh L_f deficiency leading to impaired architectural response to training (Timmins et al., 2017), but this was not evident. Furthermore, shorter BFlh fascicles probably have fewer in-series sarcomeres. This makes them more susceptible to being overstretched by powerful eccentric contractions (Brockett et al., 2004). Shifting of the torque curve or the torque angle relationship, is an indirect measure of sarcomerogenesis and evidence of the shift in optimum torque production towards longer lengths is controversial. This is important as this shift towards torque production in longer muscle lengths is thought to be injury protecting, as it allows the hamstrings to stretch further (Lieber and Bodine-Fowler, 1993, Brockett et al., 2001). There were no differences evident between groups although all but one player with previous injury had L_f below 10cm, suggestive that having a fascicle length less than 10cm may play a part in previous HSI, but more research is required to determine whether this was evident pre-injury or as direct result of the injury/inadequate rehabilitation.

L_f values are slightly lower than values estimated previously using trigonometric equations, in which those suffering from hamstring injury have shorter BFlh L_f than those who remain uninjured (<10.56cm) and have a 4.1-fold increased risk of injury as a result (Timmins et al., 2015). Trigonometric equations tend to overestimate muscle L_f (8-10%) but also on occasions underestimates (Franchi et al., 2019, Noorkoiv et al., 2010, Pimenta et al., 2018). These results should also be compartmentalised into discussion around the mid belly of Biceps Femoris as proximal fascicles are 38% longer than distal fascicles (Bennett et al. 2014) and have significantly greater levels of shortening during contraction (40%) than distal fascicles, where there is 1.5 times greater strain on the aponeurosis during eccentric contractions than distal segments (Bennett et al., 2014).

There are no differences in θ_p (20+/-9^0) and a review study reports angles in the literature for the BFlh to range from 0 to 28^0 (Kellis, 2018). Values reported in the current study are higher than those in a group of non-injured athletes (16.4-18.1^0) (Pimenta et al., 2018). This variability in the literature can be attributed to the different areas of the muscle having been measured within studies as proximal, mid and distal segments have all been reported (Seymore et al., 2017). Greater angles of pennation allow a greater number of fascicles to be packed into the muscle, parallel to each other to increase force production (Aagaard et al., 2001). Current scans are via EFOV while the majority of other studies use trigonometric equations in which they under-estimate fascicle angle (8%–9%), compared to EFOV techniques. Strength training and detraining can influence θ_p up to 12% (Duhig et al., 2019), it is highly sensitive and can change after 4 weeks, it can also be influenced during the day with increases in pennation evident as a consequence of muscle contraction. The current cohort had very little access to gym equipment during a national lockdown for 16 weeks and a consideration which interpreting the current results. Previous HSI is also a consideration as θ_p of the fascicles underneath the muscle scar and site of injury shows a change of 51.4% and is present 1 year after injury (Kellis et al., 2016).

BFlh L_f was strongly related to Iso_{BI} and moderately related to Iso_{UNI} but not to NB_{Ecc} in players with previous HSI. Isometrics and BFlh L_f was the strongest indicator of previous HSI with 62.5% of players with previous HSI having fascicle lengths shorter than 9.7cm (mean of non-injured group) and strength levels below 415N (mean of non-injured group) (Figure 7.4). To date low levels of isometric knee flexor strength have not been associated with future HSI (Timmins et al., 2016b), it would be interesting to investigate if this is the case with the novel isometric tests, as per the findings for retrospective injury. Running is the main mechanism of injury in Gaelic football (73%) (Roe et al., 2018b) in which injury occurs in late stance/swing phase (Yu et al., 2008). It is widely regarded these are the phases in which peaks for muscle activation occur (Chumanov et al., 2011) and also where the hamstrings can reach their maximum length (Thelen et al., 2005a). The isometric testing may expose the vulnerability for injury by testing in a position in which the hamstrings are in their position of greatest risk and may help explain the disparity between eccentric and isometric testing and provide an insight to the greater relationship to BFlh L_f.

Therefore the hypotheses proposed in which:

- BFlh Lf is shorter in players with previous HSI is rejected.
- θ_p is greater in players with previous HSI is rejected.
- L_f, θ_p has a strong association with NB_{Ecc}, Iso_{BI}, Iso_{UNI} strength in players with previous HSI is rejected.

7.5 Summary

A trend towards shorter fascicles in the dominant limb of previously injured players is reported and a good relationship between fascicle length and isometric testing. Isometric testing is useful in discerning for deficits in previous HSI due to the similarity of the testing method to the mechanism of HSI. Given this sensitivity of isometric assessment, given that it is quick and safe to perform one would wonder as to its application for muscle injury classification following injury as clinical assessment involves specific clinical tests with very little co-corroboration with objective strength markers. Such information may inform the clinician to make a more accurate diagnosis and prognosis following HSI.

7.6 Limitations

- EFOV is not widely available and only the most up to date US scanners have this function.
- During EFOV scanning the US user is required to be highly competent to determine the specific anatomy of the BFlh (Figure 7.1) while they also need to be skilled in oscillating the transducer head to ensure the transducer is 1) moved smoothly through range for a high scan quality 2) that the downward pressure does not distort the epidermis and cause distortion of the underlying fascicle and 3) perpendicular to the aponeurosis to ensure the fascicle remains in view throughout the proximal to distal regions. Nine scans were not of sufficient quality when exported to Image J in which the whole fascicle was not in view.

STUDY 6

Isometric Assessment and the Classification of HSI following acute injury.

8.1 Introduction

Acute HSI has been diagnosed by muscle injury classification systems to provide a diagnosis of HSI, however there is limited evidence within these classifications systems for predicting return to play following HSI (Reurink et al., 2015b). Clinicians have used a number of tests to classify acute muscle injury and these have included the subjective visual analogue scale (VAS) of pain (Boonstra et al., 2008), range of motion (Askling et al., 2006), active knee extension (AKE) and passive straight leg raise (PSLR) (Schneider-Kolsky et al., 2006). The clinical diagnosis of acute HSI using these tests has previously been described (section 2.4). Up to now strength testing has been used widely to investigate underlying pathologies and risk of HSI with little relationship to muscle injury classification. There is very little or no objective strength testing available to support clinical examination and diagnosis of HSI and there is a need for relevant tests with discriminative and predictive ability (Heiderscheit et al., 2010). Such data would aid the clinician and strengthen the decision making process with in HSI diagnosis and classification.

The aim this study was to investigate the diagnostic accuracy of Iso_{BI} and Iso_{UNI} in the clinical diagnosis of HSI. The objective was to determine 1) whether there was a difference in ISO_{BI} assessment between the involved and un-involved sides in grade 0, I and II injuries following acute HSI 2) whether there was a difference in ISO_{UNI} assessment between the involved and un-involved sides in grade 0, I and II injuries following acute HSI 3) the level of agreement between hamstring classification and ISO_{BI} 4) the level of agreement between hamstring classification and ISO_{UNI}

8.1.1 Hypotheses

- ISO_{BI} strength is lower in players in the involved side in Grade 0, I and II injuries following acute HSI.
- ISO_{UNI} strength is lower in players in the involved side in Grade 0, I and II injuries following acute HSI.
- ISO_{BI} strength has a strong agreement, to subjective classification of Grade 0, I and II injuries following acute HSI.
- ISO_{UNI} strength has a strong agreement, to subjective classification of Grade 0, I and II injuries following acute HSI.

Note:
This study was undertaken from June-December 2021 following the first national COVID-19 lockdown.

8.2 Methods

8.2.1 Participants and study design

A total of 30 HSI were tested 0-7days following acute hamstring injury. 30 club Gaelic footballers who presented at a private clinic following an acute onset of posterior thigh pain in either training or competition were invited to participate in the study. These players were unable to train or participate in Gaelic football at the time of their injury. The initial hamstring injury diagnosis was made by a lead clinician and verified by a clinical colleague. Screening and ethical approval as per studies 1, 2 and 3.

8.2.2 Muscle Injury Classification

Hamstring injury was defined as a posterior thigh injury, to the hamstring muscle group and were indirect muscle disorders of the musculotendinous complex of biceps femoris, semitendinosus and semimembranosus. Injuries were graded according to the signs and symptoms as described by (Pollock et al., 2014). The myofascial/musculotendinous/intra-tendinous component of the classification system was omitted and injuries referred to as Grade 0, I, II, III and IV, as MRI is used to determine the component of HSI.

8.2.3 Inspection and Palpation

The hamstrings were visually inspected for discoloration, bruising and ecchymosis. The hamstring muscle was palpated for focal tenderness and the point of local tenderness defined and compared to the non-injured side as it has a good correlation with MRI (Askling et al., 2007). This was also undertaken to determine the proximity to the muscle tendon junction as this is associated with more severe clinical issues (Balius et al., 2009). Time to pain free walking was also investigated as pain greater than 24 hours post injury requires at least 3 weeks to return to play (Warren et al., 2010).

Figure 8. 1: Ecchymosis following hamstring strain injury.

8.2.4 Active knee extension

Active knee extension test has a reliability of 0.89 (Reurink et al., 2013) and was measured with the participant supine on the examination table. The injured leg is fixed flat on the examination table. The opposite and tested side is then flexed to 90 degrees and measured with a Leighton flexometer. The lateral femoral condyle being vertically above the most distal palpable point of the greater trochanter and the ankle relaxed. The examiner holds the tested leg in place, just below the knee to stabilize and maintain 90 degrees and the athlete asked to extend the knee to a maximal tolerable stretch. This was a point in which there was a mild stretch of the hamstring with no shaking. The angle between the femur and tibia was measured by pacing the goniometer directly on the lateral joint line and aligning both axis of the goniometer with the lateral central line of both the femur and the tibia. This is then repeated on the injured side. With the injured side the point at which the onset of pain occurred was used to determine maximal tolerable stretch.

8.2.5 Passive straight leg raise

PSLR was measured with the participant in supine position on the treatment table (Maniar et al., 2016). The injured leg was fixed to the table and the non-injured side measured. The flexometer was applied by being fastened to the tested leg at the knee and aligned with the lateral joint line and centred at 0 Degrees. The participant relaxed the leg at which point the clinician lifted the leg slowly vertically with the knee in full extension. The point at which the participant experienced a mild stretching with no shaking was measured via the Leighton Flexometer and the angle recorded. This process was repeated on the injured side and maximum tolerable stretch and angle was measured prior to the participant feeling any degree of pain/discomfort as per the non-affected side.

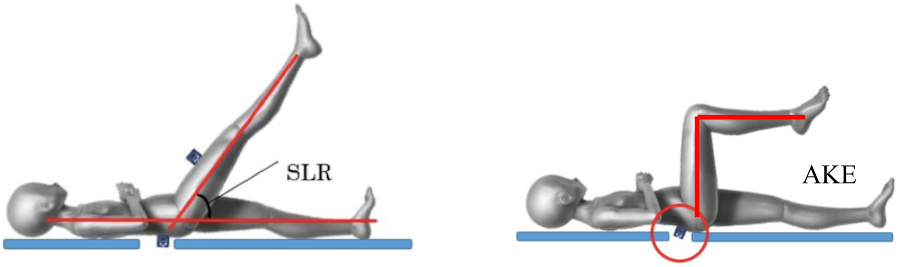


Figure 8. 2: *Straight Leg Raise and Active Knee Extension Tests.*

8.2.6 Current Manual Muscle testing method and Visual Analogue Scale

With patients prone on the treatment table the test was performed on the un-injured side (Schneider-Kolsky et al., 2006). With a neutral hip the participant was instructed to flex the knee to 15° where the tester applied force in a perpendicular direction to the tibia, directly to the posterior calcaneus. Force was applied gently and steadily for 2-3secs which resulted in the participant producing maximum force in resistance against the examiner. This test was then repeated on the injured side in which the knee was flexed to 15° once again force was applied gradually and steadily. The participant was instructed to drop the heel to the bench once pain become too uncomfortable or intolerable. The participant then scored pain via the visual analogue scale which has been previously proven to be valid, reliable and responsive

(Crossley et al., 2004). The VAS for pain consisted of a 100 mm line, labelled at the left end as ‘no pain’ (0 mm) and at the right end as ‘very severe pain’ (100mm). Patients were asked to draw a vertical mark. All scores were then rated out of 10.

8.2.7 Strength assessment

$\mathrm{Iso}_{\mathrm{UNI}}$ and $\mathrm{Iso}_{\mathrm{UNI}}$ strength battery were undertaken as per studies 2 and 3.

8.2.8 HSI reporting

As per studies 1 and 2.

8.2.9 Data analysis

Data was analysed using SPSS software package V.18.0 (SPSS Inc, Chicago, Illinois, USA). The mean and SD of age, mechanism of injury, dominant side and force calculated for both the injured and un-injured groups was determined. The data was examined for normality and an independent T-test was used to compare the injured limb to non-injured limb. Subjective clinical assessments, coupled with the objective clinical signs, can serve as a ‘criterion measure’ for the presence of HSI in our series of athletes. Levels of agreement was used and correlation between isometric strength and hamstring grade was performed using Spearman rank order correlation statistics.

8.3 Results

8.3.1 Participant and injury details

A total of 30 players (age 26±5) took part in the study during which 30 HSI were sustained during the playing season (August-November 2020). The main mechanism for injury was high speed running (which accounted for 77% of all injuries), followed by overuse injury 11.5%) and picking a football off the ground/other (11.5%).

8.3.2 Range

In PSLR the involved limb ratios were 0.99±0.06, 0.92±0.11 and 0.86±0.13 for Grade 0, I and II. In the active 90/90 test the involved limb ratios were 0.98±0.08, 0.91±0.05 (p>0.05), 0.90±0.04 (p>0.05) Grade 0, I and II.

8.3.3 Strength

In the bilateral isometric test there was no difference (p>0.05) between the involved and uninvolved sides for grade 0 (224±42 v 246±59N), I (204±67 v 240±49N), and II (137±56 v 163±36N), receptively. The opposite to opposite ratios were 0.94±0.19, 0.86±0.26 and 0.84±0.25 for Grade 0, I and II. In the unilateral isometric test there were significant differences (p<0.05) between the involved and uninvolved sides for grade 0 (351±99v 402±74N), I (252±101v 380±99N), and II (187±62v327±58N), receptively. The involved limb ratios were 0.87±0.17, 0.66±0.18 and 0.59±0.20 for Grade 0, I and II.

Table 8. 1: *Unilateral isometric strength for involved versus uninvolved side (p<0.05). You will see the involved side is significantly weaker at all muscle grades.*

Units	Involved side	Un-Involved side	Ratio	P-Value
Grade 0	351±99	402±74	0.87±0.17	0.043
Grade I	252±101	380±99	0.66±0.18	0.003
Grade II	187±62	327±58	0.59±0.20	0.016

Table 8. 2: *Clinical assessment and <10% bilateral deficit in isometrics strength and hamstring strain injury. You will see in the ISO$_{UNI}$ test that in 80% of all cases there was greater than a 10% deficit. This criterion was applied as a strength deficit less than 10% is widely accepted a s cut off to return to play.*

Bilateral Isometrics			**Uni-lateral Isometrics**		
	Total			**Total**	
	N	**%**		**N**	**%**
Positive	27	57	**Positive**	24	80
Negative	13	43	**Negative**	6	20
Total	30	100	**Total**	30	100

In 27 cases (57%) there was a greater than 10% deficit in bilateral isometric strength with associated hamstring injury. In 24 (80%) of the cases there was a greater than 10% deficit in unilateral isometric strength with associated hamstring injury.

Table 8. 3: *Correlation between clinical assessment of hamstring injury and isometric strength.*

	Grade r[a]	P
Unilateral Iso Test	0.553	<0.01
Bilateral Iso Test	0.350	<0.06
Bilateral Ratios	0.163	<0.04
Unilateral ratios	0.587	<0.01

[a] Spearman rank correlation

Isometric strength during the clinical assessment was highly correlated with unilateral isometric strength and the grade of hamstring injury (r=0.002, P< 0.01) with moderate correlations for the bilateral test (r=0.058, P<0.06). The ratio during the clinical assessment was highly correlated with unilateral isometric ratio and the grade of hamstring injury (r=0.587, P< 0.01) with lower correlations for the bilateral test (r=0.163, P<0.04) (Figure 8.3 and Figure 8.4).

Table 8. 4: *Bilateral Ratio and grading of hamstring injury.*
You will see the greatest bilateral deficits in the ISOUNI test.

	Bilateral	Unilateral
Grade 0	0.94±0.17	0.88±0.18
Grade I	0.86±0.26	0.66±0.18
Grade II	0.84±0.25	0.59±0.20

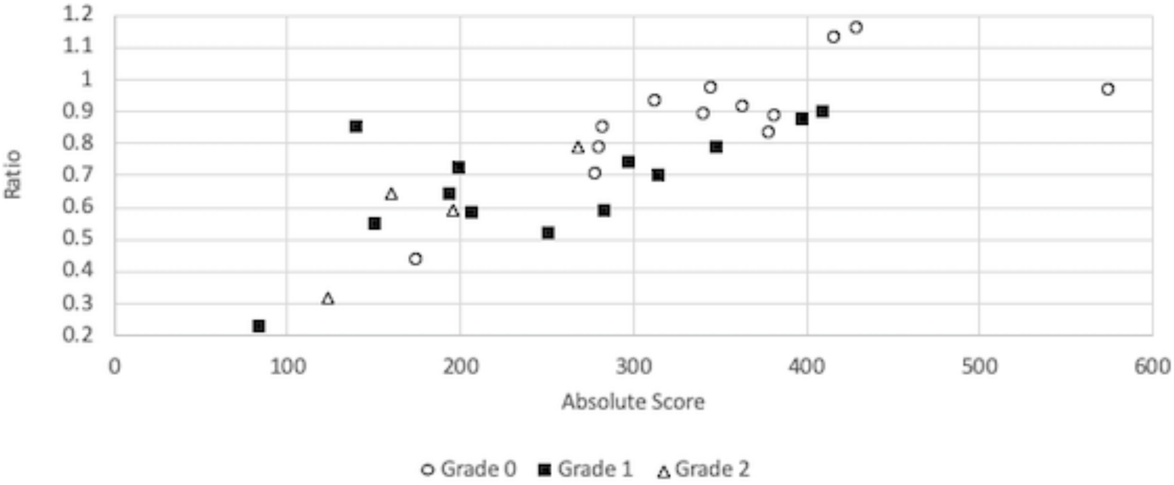


Figure 8.3 Scatterplot of the ISO_{UNI} bilateral ratio and HSI classification.

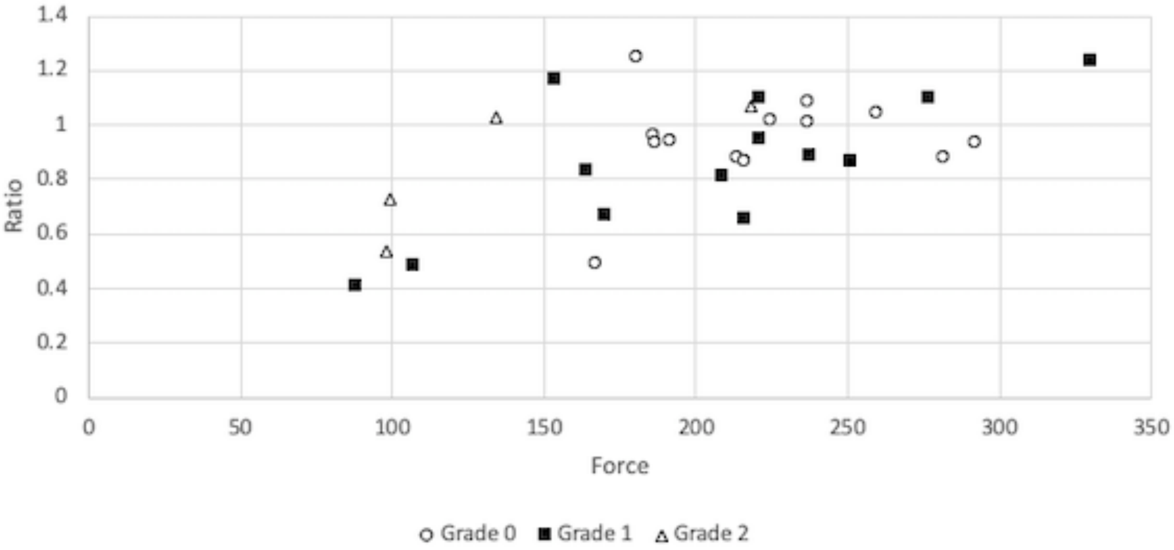


Figure 8.4 Scatterplot of the ISO_{BI} bilateral ratio and HSI classification.

8.4 Discussion

The purpose of this study was to investigate isometric strength measurements in the involved and un-involved limbs following the initial classification of HSI and examine the diagnostic accuracy of these isometric tests for HSI. The findings from the study indicate that 1) The ISO_{uni} of the involved side was significantly weaker in comparison to the uninjured limb for grade 0, I and II HSI classification 2) There was a high level of agreement and correlation between ISO_{uni} ratios and clinical assessment in the classification of HSI.

Lower Iso_{UNI} strength exists in the involved side in comparison to the un-involved side for grade 0, I and II HSI. NB_{ECC} testing was omitted from the current testing as it was not safe to undertake a Nordic hamstring exercise with acute hamstring injury. Excessive strain and structural damage to myofibers and subsequent detachment from the connective tissue (Garrett et al., 1988) with the presence of muscle scarring altering the in vivo mechanisms of muscle function (Silder et al., 2010). The Iso_{UNI} test isolates and assesses muscle function in a long lever 150° position with the contralateral hip in extension, similar to the mechanism of injury in late swing phase/early stance (Chumanov et al., 2012, Orchard, 2012, Schache et al., 2010). The current research indicates that the Iso_{BI} is not as sensitive in detecting asymmetries associated with underlying weaknesses as the Iso_{UNI}, however more research is required.

In 57% and 80% of the cases both Iso_{BI} and Iso_{UNI} deficits of greater than 10% existed with clinical diagnosis of HSI. Usually bilateral deficits above 10% are associated with muscle dysfunction. This agreement became stronger as the level of grading increased with the Iso_{UNI} test throughout the various grades more accurate in grading HSI in club Gaelic footballers. Isometric strength and hamstring grading from clinical assessment is highly correlated with Iso_{UNI} strength and the Iso_{UNI} ratio. It is widely accepted that between limb imbalances in eccentric strength increase the occurrence of hamstring strain injury (Orchard et al., 1997, Jönhagen et al., 1994, Croisier et al., 2008, Fousekis et al., 2011, Bourne et al., 2015). Bilateral deficits are reported to exist prior to HSI in Gaelic footballers of 9.2% ± 7.2 and 8.9% ± 6.9 (Roe et al., 2019), 20% of elite rugby union players having imbalances ≥15%

experience an in-season hamstring injury and players with this characteristic were 2.4 times more at risk compared to those without (Bourne et al., 2015). In study it has been identified that imbalances of ≥15% are associated with 1.55 times risk of injury. These differences have been associated with previous injury (Lee et al., 2009, Opar et al., 2013c), preference for the dominant limb (Blache and Monteil, 2012) and fatigue during match play (McCall et al., 2015a). In the Iso$_{BI}$ test ratios of 0.94,0.86 and 0.84 are reported for grade 0, I and II. Iso$_{UNI}$ strength is the more accurate of the novel isometric tests for HSI classification with reported ratios of 0.88,0.66,0.59 for grade 0, II and II respectively. The Iso$_{UNI}$ protocol places the contralateral limb in an extended position also introduces a moment arm and may mechanically preload the tested leg and influence torque production. This may increase the vulnerability of the hamstrings as it becomes pre-loaded. Activation patterns of the hamstrings vary with hip position and hip and knee forces significantly increase as fascicle lengths within the hamstring are lengthened (Kwon and Lee, 2013). In the case of the injured hamstring this position may expose the underlying weakness and highlight underlying strength deficits, however the effect of extending the hip and its effect on the contralateral hamstring are not fully understood. Given the level of differences in absolute strength between the involved and uninvolved sides, agreement and correlation in the unilateral test Iso$_{UNI}$ ratios of 0.88,0.66,0.59 are advocated to corroborate clinical diagnosis and grading of 0, I and II hamstring injuries.

Clinical assessment was undertaken by two clinicians with a combined experience of 20+ years of experience in the sports medicine field. Subjective examination was undertaken as previously outlined, without the corroboration of MRI. It is debated and it has been reported it is not required for minor or moderate HSI in professional footballers (Schneider-Kolsky et al., 2006) and also there is inconsistency within the literature as its prediction for return to play (Reurink et al., 2015b). However as MRI is considered by some as the gold standard in relation to HSI diagnosis, particularly for more deeper intramuscular/tendon diagnosis, it would also be beneficial to correlate this Iso$_{UNI}$ with MRI to further develop the merits of unilateral ratios in the diagnosis of HSI.

Therefore the proposed hypotheses in which:

- ISO$_{BI}$ strength is lower in players in the involved side in Grade 0, I and II injuries following acute HSI is not supported.

- ISO_{UNI} strength is lower in players in the involved side in Grade 0, I and II injuries following acute HSI is accepted.
- ISO_{BI} strength has a strong agreement, to subjective classification of Grade 0, I and II injuries following acute HSI is rejected.
- ISO_{UNI} strength has strong agreement, to subjective classification of Grade 0, I and II injuries following acute HSI is supported

8.5 Summary

Isometric testing utilising the ISO_{UNI} is safe and can be used in the clinical assessment of muscle grading following acute HSI, during which greater bilateral strength deficits exist in the ISO_{UNI} test.

8.6 Limitations

- Clinical assessment of hamstring injury is based on the experience of the clinician and differential diagnosis can be affected as a result. In high performance and elite environments this is corroborated further by MRI to ensure an accurate diagnosis and prognosis. MRI was not used in the current study as it is expensive to perform.

Chapter 4

Synthesis of Findings

The initial research indicates that older players with previous hamstring strain injury history have the greatest risk of HSI injury. NB_{Ecc} strength is not predictive of previous HSI. Both the bilateral (ISO_{BI}) and unilateral (ISO_{UNI}) isometric tests for isometric knee flexor strength were moderately high. ISO_{BI} strength testing better identifies those with residual strength deficits following HSI in the previous season, with strength levels below 150Nm suggestive of previous HSI, whereas NB_{Ecc} knee flexor strength deficits are not evident. Residual Iso_{UNI} and Iso_{BI} and eccentric IKD torque weaknesses exist in previously injured players with IKD ratios for opposite hamstring to hamstring, conventional and functional ratios were all found to be lower. There was a trend towards BFlh L_f and not θ_p in those with previous HSI with L_f highly related to isometric strength and not NB_{Ecc}. There is a high level of agreement and correlation between isometrics and the Iso_{UNI} opposite to opposite limb ratio for the classification of HSI.

Covid-19 had a direct impact on studies 2, 4, and 5. Initially these studies were designed to be retrospective and prospective in design. Study 1 remained unchanged in which it looked at prospective and future injury, study 3 a reliability study and also study 6 which was undertaken in the private clinic. Studies 2,4 and 5 were affected by the volume of games as the rate of hamstring injuries in Gaelic football is greatest in match-play (8.2 / 1000hrs) (Roe et al., 2016). Competitive games were reduced by 60% (2020) and to just over 50% (2021) and training restrictions were in place which directly affected the prospective data (Table 9.1). This affected the injury rate with players having less exposure to both games and training, while also having greater time to recover. Prospective data in these studies were analysed, but with no statistical power, due to the cohort size.

Table 9. 1: *Outline of Covid 19 and study design – you will notice truncated seasons in 2020 and 2021.*

	2019 **(Study 1)**	**2020** **(Study 2 + 3)**	**2021** **(Studies 4 +5)**
Covid 19	No restrictions	2 National lockdowns March – June July – December (Restrictions) December - March	Lockdown lifted in March March -December (Restrictions)
Club Playing Season	Preseason January -March March – November 20 Games in 32 weeks 1 game per 11.2 days	August – September No preseason 8 games in 10 weeks 1 Game per 8.8 days	August – November No preseason 11 games in 16 weeks 1 game per 10.2 days

There was no relationship between pre-season and late in-season peak NB_{ECC} torque measures and the risk of HSI. Players who suffered HSI during the season in Study 1 did not differ in pre-season NB_{Ecc} strength between the involved (125 ± 25 Nm) and involved side (125 ± 31 Nm). Similarly in study 2, the preseason group with previous HSI (136 ± 34 Nm) was similar to the non-injured group (136 ± 32 Nm) and this was also reported in Study 4. Previous to beginning this research, this was not evident in the literature, but it has also been reported more recently (Opar et al., 2021), (Smith et al., 2021), (Roe et al., 2020)**.** A minimum of 120Nm for HSI is suggested as a result of the RR in relation to future HSI, however cut off points are difficult to translate into normal sporting practise as there are many variables and risk factors associated with HSI. Furthermore, this does not necessarily reduce the risk of injury particularly as the mean of both the injured and uninjured groups were 125-126Nm (Pre-season) and 124-134Nm (In-season). In future it would be of benefit to report NB_{ECC} strength as torque in order to compare GF players of varying limb lengths (Table 9.2).

Table 9. 2: *NB_{ECC} Absolute and relative torque of (Means) reported for study cohorts.*
You will see preseason NB_{ECC} strength for the two cohorts to range between 125-143Nm in pre-season.

	Preseason	**In-Season**
Study 1 (n=213)	125-126 Nm	124-134 Nm
	1.54-1.58 $Nm.kg^{-1}$	1.56-1.7 $Nm.kg^{-1}$
Study 2 (n=70)	136-143 Nm	
	1.66-1.75 $Nm.kg^{-1}$	

Gaelic players range in limb lengths and body mass which is an important consideration (4N increase in maximum eccentric knee flexor strength per 1kg increase in body mass). This equates to a 40N difference between Australian rules footballers and rugby players as Australian rules footballers are 10kg lighter than rugby players. Absolute knee flexor strength is difficult to interpret as a result, as comparison to other sports is not possible. The Nordbord via $\mathrm{NB}_{\mathrm{ECC}}$ strength testing is a useful device for tracking strength changes longitudinally as indicated in our current research, in which there was a 6% increase in all limbs apart from the involved limb in those players who sustained a HSI, with higher in-season strength values evident in Table 9.2. This may be as a result of exposure and individual adaptions to strength training and sprinting, as we know both have been seen to increase $\mathrm{NB}_{\mathrm{ECC}}$ strength (Timmins et al., 2021). Early in Study 1 age, but more importantly, previous HSI (in which injured players are 33 times more likely to sustain a HSI) are more dominant risk factors and further validate these widely accepted risk factors. A recently published study by (Smith et al., 2021), has reported player's age greater than 25 years (OR = 2.9, $p < 0.05$) and player's with a previous HSI within the previous year (OR = 3.7, $p = 0.01$), or greater than 1-year (OR = 3.6, $p = 0.01$) are more dominant risk factors than $\mathrm{NB}_{\mathrm{Ecc}}$ strength, and has no association with HSI. It is recommended that $\mathrm{NB}_{\mathrm{Ecc}}$ be used as a longitudinal strength measure (for eccentric strength in general), as it does not provide any value in terms of previous HSI and its role in pre-season can be debated.

Early in the research this information posed more questions, than answers, around providing a solution to the issue surrounding strength testing and HSI risk. As a result, alternative solutions were sought by investigating the underlying kinematics and kinetics and the mechanism of injury. The hamstrings in GF players are required to withstand large forces of up to 5200 N (Table 9.3) and the difficulty in ascertaining the precise time of injury is due to high running speeds, where deceleration during the late swing phase of high-speed running usually occurs in less than 250 milliseconds (Rodríguez-Rosell et al., 2018). However, there is a general consensus that HSI is likely to occur in either late swing phase or early stance (Chumanov et al., 2011, Chumanov et al., 2012, Orchard et al., 2012, Schache et al., 2010, Yu et al., 2008, Heiderscheit et al., 2005, Schache et al., 2009), in which there is between $140\text{-}150^0$ of knee extension (Kenneally-Dabrowski et al., 2019). Therefore, considering a $\mathrm{Iso}_{\mathrm{BI}}$ test in which there is an upright posture with 150^0 of knee extension would be more reflective of the mechanism of HSI during the running gait cycle.

A moderate to high reliability is reported for Iso_{BI} (0.89, ICC=0.79-0.94). Iso_{BI} force and torque all differed significantly in previously injured limbs with a moderate effect size ($p<0.01$, d=0.68-0.74) but not NB_{ECC}. This difference in ISO_{BI} and NB_{ECC} testing can be attributed to the fact that peak values are ascertained from 150° position in the case of the Iso_{BI} method and between $103\text{-}126^0$ in the NB_{ECC} method. NB_{ECC} uses gravity while the isometric testing is in a upright position, the gluteal is required to contract with the hamstrings in the NB_{ECC} test whilst in the Iso_{BI} the hamstrings are isolated. With a large increase in muscle tendon unit length and the greatest stretch in the BF (112%) know to occur whilst running, it may explain the sensitivity of the Iso_{BI} which is more biased towards assessment in outer range or longer muscle lengths. Moreover, this now advanced the field whereby residual differences are now reported to exist in a novel ISO_{BI} method and required further research. This was a further clue to consider and further converged the research question towards this isometric concept and position of testing.

Very rarely is the position of the contralateral hip considered and it is important to do so as it better simulates the posture (20^0 of hip extension) while running where the contralateral or non-weight bearing limb during late swing/early stance is in $15\text{-}25^0$ of hip extension (Kenneally-Dabrowski et al., 2019). This also introduces co-contraction of the gluteal with the hamstring during hip extension. Previous researchers have attempted to investigate this either in a supine or prone position with the tested limb at 150^0 of knee extension, mirroring the long lever position, however the contralateral limb has always remained in flexion (Wollin et al., 2016, McCall et al., 2015b). This is an important consideration to testing as this would alter the centre of gravity of the subject and create an extension moment around the hip more similar to running (Figure 9.1). Introducing extension (20^0) into the contralateral hip, the kinaesthetic feedback of the subject was that the hamstring became “tighter” and ‘longer”, even though the knee angle (150^0) of the testing limb did not change (Fig 9.1). We can speculate that this maybe reflective of an increase in the intrinsic muscle tendon unit length change similar to that noted (112%) during the running cycle. This test now augmented the bilateral testing protocol which also required further investigation as to its appraisal of both retrospective and prospective HSI.

Figure 9. 1: *Isometric unilateral joint positions.*

*Y*ou will notice the similarities between the ISOUNI test and the running gait cycle (Late swing) in which there is a long lever position in the tested limb (lead limb in the running gait cycle) while the contralateral limb is in extension in both images. You will also notice that the contralateral knee is supported (on a bench where this is not the case when running). This test does not account for various stride lengths in which hip angles differs between players with different limb lengths at various speeds of running.

Subsequently both isometric tests were used as part of strength battery in Study 4 which also included NB_{ECC} and an IKD methodology. In the ISO_{BI} injured players were on average 20Nm (15%) weaker than their non-injured peers in pre-season. These deficits were even greater in the ISO_{UNI} 29Nm (15%) between groups (Table 9.3). The ISO_{UNI} isolates the injured limb and it also places the contralateral (non-tested) hip into extension similar to the joint angle seen in late swing/early stance of the running gait pattern. The higher torque values generated in the unilateral test (30% greater) could be due to the extension of the contralateral hip, creating a greater moment arm about the axis of rotation (hip) which allows for greater torque production through the point of application of force (ankle).

Table 9. 3: *Isometric Absolute and relative torque of (Means) reported for study cohorts.*

	Injured	**Non Injured**
Study 2 ISO_{BI} (n=70)	120 ± 29 Nm	142 ± 31 Nm
	1.49 ± 0.39 $Nm.kg^{-1}$	1.76 ± 0.4 $Nm.kg^{-1}$
Study 4 ISO_{UNI} (n=49)	156 ± 28 Nm	185 ± 34 Nm
	1.92 ± 0.38 $Nm.kg^{-1}$	2.33 ± 0.31 $Nm.kg^{-1}$

The ISO$_{UNI}$ test elicits greater force production than both the NB$_{ECC}$ and ISO$_{Bi}$ (Table 9.4). A similar trend exists in a recent study in Alpine skiers for NB$_{ECC}$ (5.24-5.49 Nm.kg^{-1}) and a unilateral isometric testing method (5.58-5.88 Nm.kg^{-1}) on the nordbord in a prone position at 120^{0} of knee extension. It is unclear as to why this is the case as one would expect greatest force to occur during eccentric contraction. It could be reasonable to speculate that 1) in the unilateral method the joint moments and increased contralateral lever length combined with two points of contact (arms on the bar, contralateral knee on the pad/seat) may provide the athlete with an ability to generate greater force than both the NB$_{ECC}$ and ISO$_{Bi}$ 2) secondly in relation to the NB$_{ECC}$ breakpoint varies and the lever length maybe a relevant factor. Moreover it has been reported isometric force at 30^{0} of knee flexion measured on a force plate is not correlated with NB$_{ECC}$ force (Trigwell 2019). At this juncture both the ISO$_{BI}$ and ISO$_{UNI}$ had advanced the field in terms of screening for previous HSI, it is unfortunate that Covid-19 has prevented analysis with respect to future injury.

Table 9. 4: *Forces (Nm;Nm.kg^{-1}) in the NB$_{ECC}$ and Isometric tests for studies 2 and 4. You will notice relative data ranges for uninjured players from 1.33-1.66, 1.24-1.69 for both the NB$_{ECC}$ and ISO$_{Bi}$, respectively and the greatest force in the ISO$_{UNI}$ (2.33 Nm.kg^{-1}).*

Injured			**Un-Injured**		
NB$_{ECC}$ Nm;Nm.kg^{-1}	**ISO$_{BI}$ Nm;Nm.kg^{-1}**	**ISO$_{UNI}$ Nm;Nm.kg^{-1}**	**NB$_{ECC}$ Nm;Nm.kg^{-1}**	**ISO$_{BI}$ Nm;Nm.kg^{-1}**	**ISO$_{UNI}$ Nm;Nm.kg^{-1}**
136 ± 34;1.68±0.49	120±29;1.49±0.39		136±32;1.66±0.35	142±31;1.69±0.38	
101±23;1.24±0.3	98±23;1.23±0.33	156±28;1.92±0.38	108±33;1.33±0.38	98±29;1.24±0.41	185±34;**2.33±0.38**

It was still worth exploring other modes of eccentric hamstring strength given the fact that HSI could be due to excessive eccentric muscle strain (Danielsson et al. 2020). Generally, throughout the literature there is little consensus around IKD and its application to HSI and is widely debated, as I have outlined (see Chapter 2). An unique IKD protocol attempted to address joint moment calculation errors surrounding the location of the centre of the joint axis in which shifts can present errors of up to 19% (Tsaopoulos et al., 2011). This included part of the solution as detailed by Baltzopoulous et al. (2012). Eccentric hamstring strength testing in passive mode, isolating the eccentric contraction in the hamstrings with no co-contraction of the antagonist during any portion of the hamstring assessment, while also undertaking eccentric testing in passive mode, to ensure a complete smooth eccentric contraction throughout range. Five of the torque metrics at 60^{0}/s were significantly lower in previously injured players . Recently it has been reported that an increase of one Newton in concentric knee flexor peak torque at 90^0/s above a cut-off point (182N) can reduce the risk of future injury by 2%-3% (Burigo et al., 2020). Even though the test is not at 90^0/s values here of 102 ± 21N and 86 ± 22 N for 60^0/s and 180^0/s respectively, are somewhat lower than those reported values by (Burigo et al., 2020). Cut-off values at times are not useful to guide the restoration of strength as a criterion following HSI (van Dyk et al., 2019). Furthermore, there are significantly lower ratios in the injured side for Hcon : Qcon_{180} and FHe_{60}:Qc_{60} and FHe_{180}:Qc_{180} when comparing to the dominant limb of the non-injured group and this has recently been corroborated for mixed ratios (Pieters et al., 2020). These ratios help to highlight underlying deficits which likely persist post HSI and contribute to the overall high re-injury rate throughout the literature. Prospectively there are no differences in any of the strength parameters in players who became injured, the condensed truncated season due to COVID-19, from a prospective point of view, been a major issue. Nevertheless, in the future it is recommended, to align the centre of the dynamometer under isometric contraction, undertake testing at 60^0/s in passive eccentric mode, to investigate concentric and eccentric peak torque and finally to compare conventional and functional ratios in respect of previous hamstring injury while also considering dynamic control profile as described in Chapter 2.

Hamstring morphology is poorly researched in Gaelic footballers and the US protocol was administered prior to the strength battery where BFlh L_f and θ_p did not differ between previously injured (8.8±1.9cm) and non-injured (9.7±1.8cm) Gaelic footballers, with the tendency towards longer muscle lengths in un-injured players, requiring further research. This advances the field in GF as this has not been reported and future longitudinal studies with larger cohorts are recommended within the sport. Lower levels of L_f in comparison to other studies are reflective of the direct measurement method. Interestingly, L_f are strongly related to Iso_{UNI} and moderately related to Iso_{BI} but not to NB_{Ecc}. Combining both Iso_{UNI} and BFlh L_f was the strongest indicator of previous HSI with 62.5% of players with previous HSI having fascicle lengths shorter than 9.7cm (mean of non-injured group) and strength levels below 415N (mean of non-injured group). Perhaps future research should concentrate on combining both US measurements and the unilateral and bilateral isometric tests in a larger cohort, over a complete playing season. In retrospect, both limbs of all players should have undergone US scan which would have also allowed us to compare injured v non-injured limbs of all players with HSI.

In a broader context, beyond the scope of this research, more robust monitoring of training and rehabilitation exercises needs to be considered, to ensure players are eliciting a training effect at longer muscle lengths. Are these exercises effective in eliciting a training response at longer muscle lengths given that fact that this has not been effectively measured ? These methods need to better simulate the mechanism of injury. Eccentric hamstring strengthening at long-muscle length is effective and has been reported to decrease pennation angle and increase fascicle length of the BFlh (Gérard et al., 2020, Marušič et al., 2020). Or diving more deeply perhaps the issue is even exercise prescription, as hip extension is the only BF dominant exercise and there is large regional proximal-distal activity patterns, which can be exercise and contraction mode dependant. Prescription is not regionally specific to the injured area and some exercises (Straight knee bridge, upright hip extension, loaded leg curls) generate only between 40-85% MVIC (Hegyi et al., 2019) may curtail the training response to protect from injury. Regular sprint training in comparison promotes larger increases in BFLH L_f (Freeman et al., 2021) and worth considering as an effective means of rehabilitation**.** The challenge moving forward is to ensure rehabilitation becomes more specific and to simulate the mechanism of injury in specific modes of testing while also ensuring this data is reliable from a scientific perspective.

Outside of this PhD, I have had the experience over the last 12 months of using the isometric tests alongside clinical assessment for acute hamstring injury in the private clinic and to also compile further data for the classification of strength (Table 9.5). Firstly, for classification of muscle grading following HSI and also to appraise muscle function while returning to play. What became apparent towards the end of the PhD was the application of the isometric bilateral and unilateral tests in assessing clinical hamstring function and grading following HSI. In clinic, experimentation began, with these tests and it became clear that they were safe and provided objective bilateral comparisons when assessing the affected side following acute HSI. It was obvious through this work (one of the final studies), that they correlated with clinical examination in the grading of HSI. Although this was not an initial research question at the outset it was a hypothesis developed during the thesis which had great clinical merit. In the final study, ISO_{uni} of the involved side was significantly weaker in comparison to the uninjured limb for grade 0, I and II HSI with bilateral ratios of 0.88,0.66,0.59 useful in the corroboration and clinical diagnosis of HSI. The ISO_{uni} is not as sensitive to injury with perhaps neural crossover a limiting factor. This can be a real useful tool for clinicians in the future as it now provides an objective measure to make an accurate diagnosis and prognosis.

In a future research paper it would be useful to incorporate MRI alongside the isometric tests to further investigate the classification of acute HSI. Since then, we have filed for patent for both the ISO_{BI}, ISO_{UNI} and developed and tested an apparatus termed “The H Rig” (Figure 9.2 and Figure 9.3)

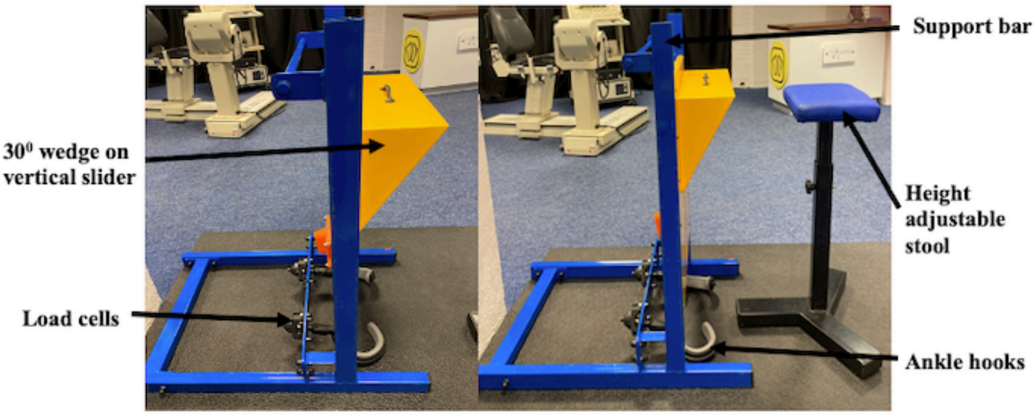


Figure 9. 2 *The H Rig.*

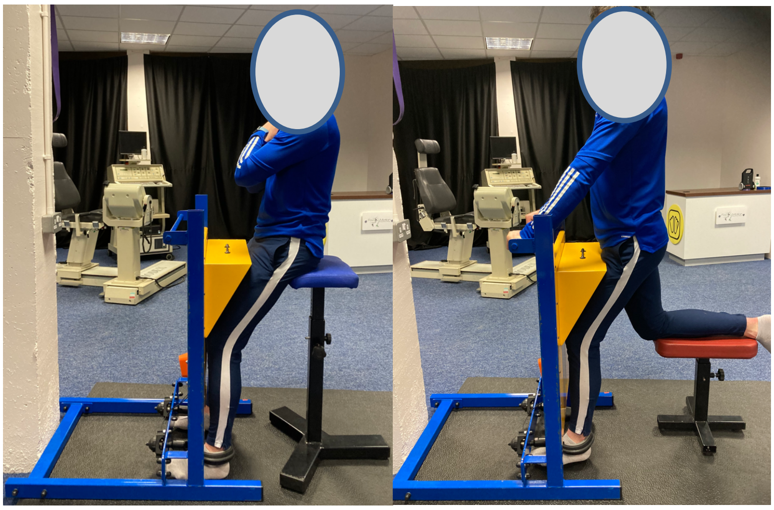


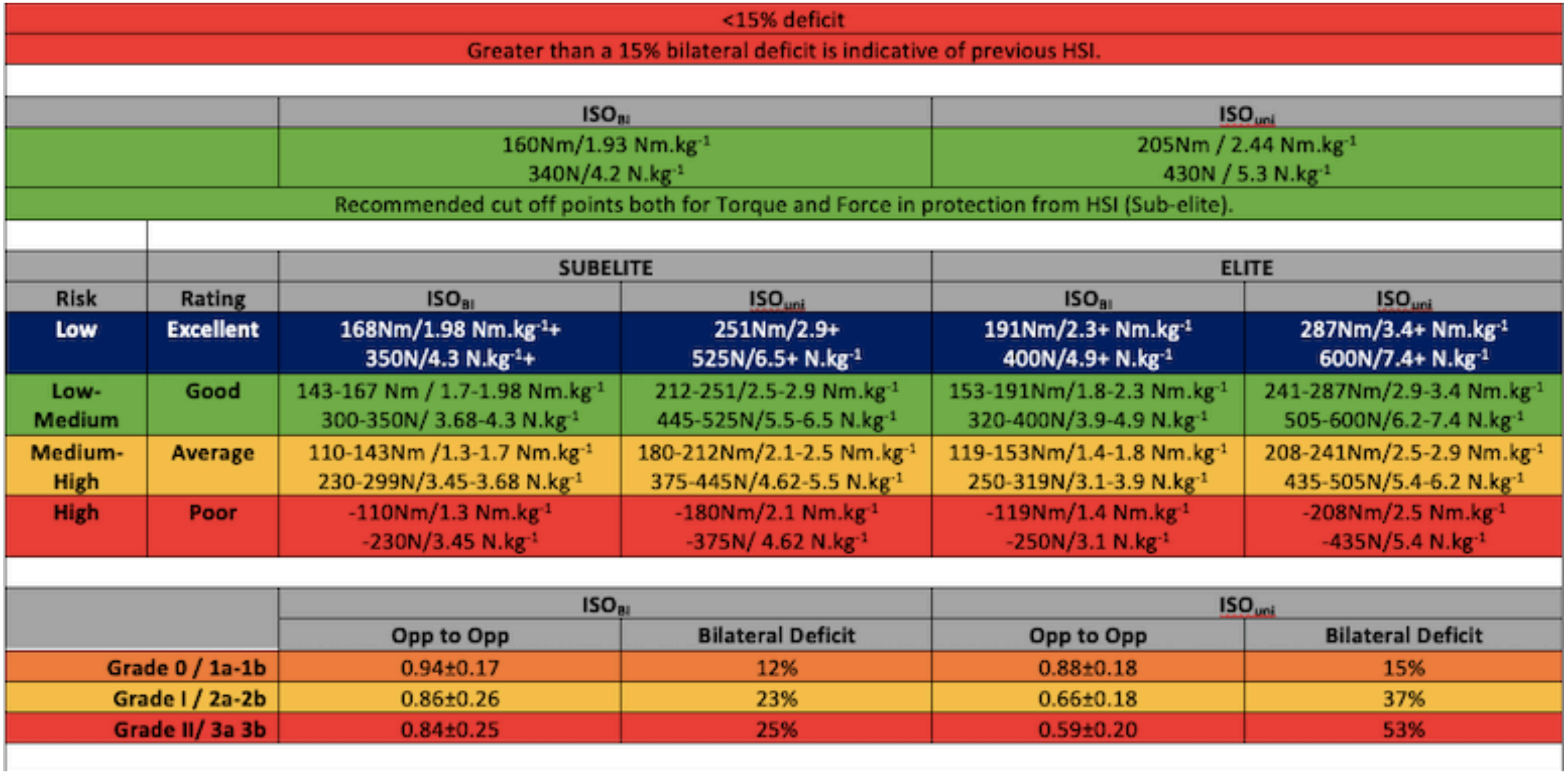
Figure 9. 3: Bilateral and Unilateral testing positions with the H Rig.

You will see the ISO_{UNI} *test position with height adjustable stool (left image) and to the right is the ISOUNI assessment of the left limb with height adjustable stool supporting the lower leg with the hip in* 20^0 *of extension.*

The clinical work to date has further developed the database to include strength values for performance, injury prevention and hamstring grading following acute HSI (Table 9.3).

Table 9. 5: *H Rig Data.*

You will notice a bilateral deficit of greater than 15% indicating previous injury and recommended cut off points based on our research for future injury, development of norms for strength classification which we have worked on clinically over the past 24 months, hamstring grading classification for Grade I, II and II HSI based on our research. These figures have been refined with additional research over the last 6 months.



<15% deficit

Greater than a 15% bilateral deficit is indicative of previous HSI.

	ISO$_{BI}$	ISO$_{uni}$
	160Nm/1.93 Nm.kg^{-1} 340N/4.2 N.kg^{-1}	205Nm / 2.44 Nm.kg^{-1} 430N / 5.3 N.kg^{-1}

Recommended cut off points both for Torque and Force in protection from HSI (Sub-elite).

		SUBELITE		ELITE	
Risk	**Rating**	**ISO$_{BI}$**	**ISO$_{uni}$**	**ISO$_{BI}$**	**ISO$_{uni}$**
Low	**Excellent**	**168Nm/1.98 Nm.kg^{-1}+ 350N/4.3 N.kg^{-1}+**	**251Nm/2.9+ 525N/6.5+ N.kg^{-1}**	**191Nm/2.3+ Nm.kg^{-1} 400N/4.9+ N.kg^{-1}**	**287Nm/3.4+ Nm.kg^{-1} 600N/7.4+ N.kg^{-1}**
Low-Medium	**Good**	143-167 Nm / 1.7-1.98 Nm.kg^{-1} 300-350N/ 3.68-4.3 N.kg^{-1}	212-251/2.5-2.9 Nm.kg^{-1} 445-525N/5.5-6.5 N.kg^{-1}	153-191Nm/1.8-2.3 Nm.kg^{-1} 320-400N/3.9-4.9 N.kg^{-1}	241-287Nm/2.9-3.4 Nm.kg^{-1} 505-600N/6.2-7.4 N.kg^{-1}
Medium-High	**Average**	110-143Nm /1.3-1.7 Nm.kg^{-1} 230-299N/3.45-3.68 N.kg^{-1}	180-212Nm/2.1-2.5 Nm.kg^{-1} 375-445N/4.62-5.5 N.kg^{-1}	119-153Nm/1.4-1.8 Nm.kg^{-1} 250-319N/3.1-3.9 N.kg^{-1}	208-241Nm/2.5-2.9 Nm.kg^{-1} 435-505N/5.4-6.2 N.kg^{-1}
High	**Poor**	-110Nm/1.3 Nm.kg^{-1} -230N/3.45 N.kg^{-1}	-180Nm/2.1 Nm.kg^{-1} -375N/ 4.62 N.kg^{-1}	-119Nm/1.4 Nm.kg^{-1} -250N/3.1 N.kg^{-1}	-208Nm/2.5 Nm.kg^{-1} -435N/5.4 N.kg^{-1}

	ISO$_{BI}$		ISO$_{uni}$	
	Opp to Opp	**Bilateral Deficit**	**Opp to Opp**	**Bilateral Deficit**
Grade 0 / 1a-1b	0.94±0.17	12%	0.88±0.18	15%
Grade I / 2a-2b	0.86±0.26	23%	0.66±0.18	37%
Grade II/ 3a 3b	0.84±0.25	25%	0.59±0.20	53%

9.1 Summary

While it was challenging during Covid-19 the aims (Chapter 1) and objectives have been achieved through studies 1-6. Initially it was planned to undertake more longitudinal follow ups and this became extremely difficult to gain access to teams and where playing seasons were cancelled and re-scheduled.

9.2 Study Hypothesis Summary

The main study hypotheses from Chapter 1 are summarised below:

Study 1 - NB_{Ecc} torque is lower in preseason in those players experiencing HSI during the playing season is rejected.
Study 2 - A novel Iso_{BI} test is reliable in measuring isometric hamstring strength in Gaelic football club players and is lower in players with previous HSI injury is supported.
Study 3 - A novel Iso_{UNI} test is reliable in measuring isometric hamstring strength is supported.
Study 4 - IKD, Iso_{BI}, Iso_{UNI} and NB_{Ecc} strength is lower in Gaelic football club players with previous HSI is rejected.
Study 5 - L_f, θ_p are both lower in players with previous HSI is rejected.
Study 6 - Iso_{BI} and Iso_{UNI} strength are both lower in players with acute HSI is accepted.

9.3 Main outcomes

- NB_{Ecc} strength is *not* predictive of previous HSI (eccentric levels below 120Nm increases HSI by 1.7 times).
- Preseason residual Iso_{BI} deficits exist in those with HSI in the previous season while 150Nm is suggestive of a cut off and 200Nm for ISO_{UNI}.
- IKD ratios including opposite hamstring to hamstring ratios, conventional and functional ratios are all lower in players with previous HSI.
- Iso_{UNI} ratios (0-7 days post injury) can provide an indication of HSI grade and classification. Iso_{UNI} ratios of 0.88,0.66,0.59 are advised to corroborate clinical diagnosis and grading of 0, I and II hamstring injuries, respectively.

- L_f (greater than 10cm), should be combined with ISO_{BI} (greater than150Nm) and ISO_{UNI} (greater than 200Nm) for HSI prevention in pre-season for club Gaelic footballers.

9.4 Future Recommendations

The NB_{ECC} should be used to measure strength longitudinally throughout the season. Alternatively, NB_{ECC} torque could be expressed relative to the break angle point as this would provide some clarity as to where in the range that peak eccentric force/torque is been measured. The ISO_{UNI} and the ISO_{BI} have advanced the field in screening for previous injury, in that they are more sensitive to previous HSI. Eccentric assessment of the hamstring should be undertaken at 60^0/s in gaelic footballers, in passive mode particularly when the athlete is not familiar/experienced with IKD. ISO_{UNI} is favoured to assist in the diagnosis of acute HSI. Strength assessment is one aspect of the multifactorial approach to HSI, highly warranted given that it is modifiable, with a new approach for screening of the posterior chain described in Figure 9.4.

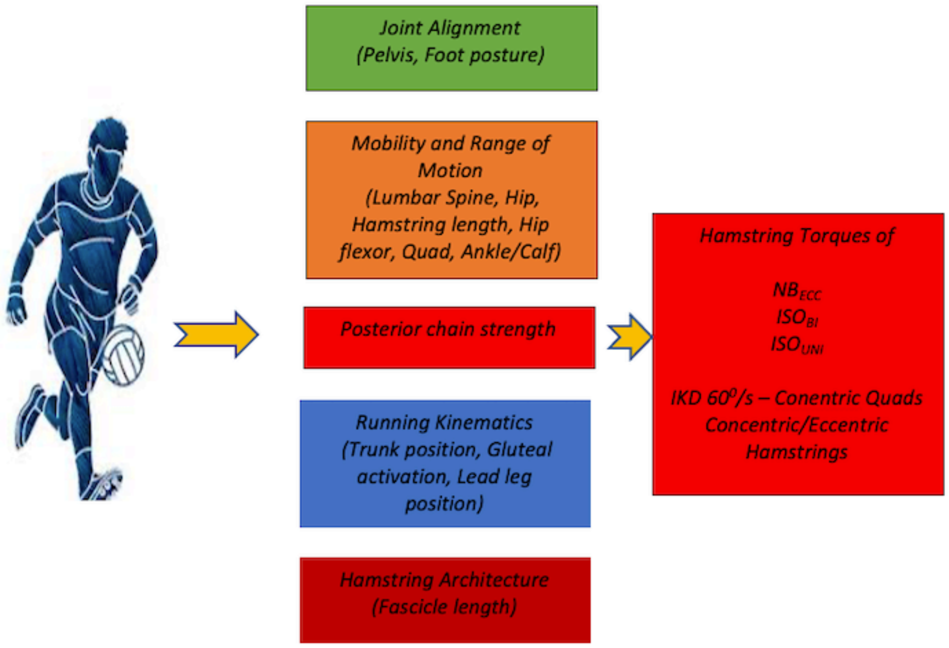


Figure 9.4 *Multifactorial screening model for Gaelic football.*

9.5 Future Research Considerations

- Implementing the novel approaches to $\mathrm{Iso}_{\mathrm{BI}}$, $\mathrm{Iso}_{\mathrm{UNI}}$, and IKD testing outlined in this study in a longer prospective study would give a greater insight as to the application of these tests for future incidence and risk of HSI.
- Considering a larger cohort for Study 4 for EFOV scanning would provide further information and address the gap in the literature both in relation to GF and also the use of EFOV for more accurate reporting of L_f and θ_p.
- More research is required on the use of passive IKD mode for the collection of eccentric hamstring torque and also the role of the central axis in minimising measurement errors.
- Test-retest reliability around IKD methodologies are advised prior to undertaking IKD assessments may help improve the reliability of data within the literature given the lack of consensus on IKD and HSI. Further investigate angle of peak torque, dynamic control profile with respect to HSI.
- Combining MRI and $\mathrm{Iso}_{\mathrm{BI}}$, $\mathrm{Iso}_{\mathrm{UNI}}$ in future studies may help further assess the relationship of these novel tests in HSI classification and grading.
- Expanding isometric assessment to also determine the rate of force development may further evolve isometric assessment and may provide some novel data with regards to recovery from HSI.
- Also, there is the potential to expand this isometric testing method for rehabilitation to support players in their recovery from injury. Isometric contraction in the initial stages rehabilitation with the H Rig may provide clinicians with objective data to safely load players in a graduated manner to optimise recovery (Prescribing a rehabilitation session at specific percentages of MVIC with live feedback on torque values).
- It may be useful to consider expanding the rationale for the isometric testing to better simulate the running gait cycle in IKD test position.

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