HA*L*HAM°: a Novel Device for Nordic Hamstring Exercise Assessment

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A thesis submitted in partial fulfilment of the requirements of

Sheffield Hallam University

for the degree of Doctor of Philosophy

February 2025

Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

2. None of the material contained in the thesis has been used in any other submission for an academic award.

3. I certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged. I confirm that I have sought and obtained copyright permission for any third-party materials included in this thesis.

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4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy, and ethics approval has been granted for all research studies in the thesis, as shown in the table below.

Thesis chapter(s)	Research study	Ethics review reference	Approval date
Chapter 3	Study 1 - Agreement of methods and terminology used to assess the Nordic hamstring exercise	ER6176646	11/05/2018

Chapter 4	Study 2 - Measuring and modifying the knee flexors torque-length relationship using the HA*L*HAM°	ER8248681	22/08/2018
Chapter 6	Study 3 - Examining the effect of feedback on metrics of the Nordic hamstring exercise	ER29609708	04/03/2021
Chapter 7	Study 4 - A cross-sectional study investigating muscle activity during incline Nordic hamstring exercise testing	ER58577692	25/09/2023

5. The word count of the thesis is 48,601

Name	Emma Sconce
Award	PhD
Date of Submission	February 2025
Research Institute	Health and Wellbeing
Director(s) of Studies	Nick Hamilton

Abstract

Hamstring strain injuries remain among the most common and recurrent injuries in sport, even in 2025. Despite a well-established base of evidence regarding the mechanism of hamstring injury, the reported incidence of injuries nearly doubling from 2001 to 2021 is alarming. While the Nordic hamstring exercise has substantial evidence supporting its effectiveness for reducing the recurrence of hamstring injuries, current assessment devices fail to adequately capture hamstring performance at extended muscle lengths, which is critical given the common injury site during the late-swing phase of sprinting. The thesis aimed to design, validate, and implement a novel hamstring assessment device capable of modifying and measuring the knee flexors torque-length relationship across Nordic hamstring exercise inclinations, preferentially targeting the biceps femoris long head at longer muscle lengths while maintaining similar torque. A prototype system (*namely the* HA*L*HAM°) was engineered to enable concurrent kinetic, kinematic and electromyographic measurement during the Nordic hamstring exercise. **Chapter 1** reviewed the impact, aetiology and mechanisms underlying hamstring strain injuries, and established the need for standardised hamstring testing. **Chapter 2** outlined the HA*L*HAM° design, detailing how it addressed the limitations of current systems, including the inability of isokinetic dynamometers to measure torque beyond 145-165° of knee extension. **Chapter 3** (**Study 1;** n=15) established the break-torque angle as a reliable and reproducible metric representing the proxy length at which muscle failure occurs, demonstrating that eccentric hamstring assessment must extend beyond peak torque alone. **Chapter 4** (**Study 2;** n=18) showed that performing the Nordic hamstring exercise at an incline significantly increased break-torque angle compared to both the flat and decline conditions, $F(2,34)=63.85$, $p<0.01$, $\omega^2=0.78$, without affecting peak torque, $F(2,34)=0.952$, $p=0.389$, $\omega^2<0.01$, indicating a rightward shift in the torque-length relationship. However, large variability in hip flexion (0.4–53.8°) and angular velocity of the knee joint at peak torque (3.6–96.3deg·s^{-1}), highlighted inconsistent individual Nordic exercise technique. **Chapter 5** presented device hardware and software upgrades, including IMU-based angular tracking validated against a gold standard Polhemus system ($r=0.99$, $p<0.0001$), and introduced a real-time biofeedback interface for exercise technique control. **Chapter 6 (Study 3;** n=24) demonstrated that biofeedback significantly improved exercise control, reducing hip flexion, $t(23)=2.98$ $p<0.01$, $d=0.51$, and descent velocity, $t(23)=3.67$, $p<0.01$, $d=0.825$ compared with verbal feedback alone. **Chapter 7** (**Study 4;** n=21) found greater bicep femoris long head activation at longer muscle lengths during incline testing, $t(20)=9.74$, $p<0.0001$, $d=1.573$ and a higher lateral-to-medial hamstring activation ratio $t(20)=7.30$, $p<0.0001$, $d=0.750$, confirming preferential recruitment of injury-prone muscle regions. **Chapter 8** consolidated the findings, evaluating the extent to which the overall thesis aims and objectives were achieved, proposing future directions and practical applications. The HA*L*HAM° is a developed, validated system capable of measuring torque-length dynamics, muscle activation, and exercise quality under multiple Nordic hamstring exercise conditions. Incline variations preferentially target the bicep femoris long head at longer muscle lengths while maintaining torque production, overcoming the key limitations of existing devices. The HA*L*HAM° system represents a significant advancement in hamstring assessment and Nordic hamstring exercise technique monitoring.

Research blueprint

Addressing the hamstring strain injury challenge

Prevalence and significance of the problem:

High rates of hamstring strain injuries in sport persist, despite established knowledge about the known mechanism of injury and evidence supporting the Nordic hamstring exercise as an effective preventative training exercise.

Key existing research findings:

The incidence of hamstring strain injuries in men's football continues to rise annually by approximately 4% per year (Ekstrand et al., 2016). The proportion of injuries diagnosed as hamstring injuries doubled from 12% in 2001/02 to 24% in the 2021/22 season (Ekstrand et al., 2023).

Hamstring strain injuries primarily affect the bicep femoris long head muscle at the proximal musculotendinous junction (83%) (Hallén & Ekstrand, 2014). Electromyography activity of the bicep femoris long head muscle is highest during the late-swing phase of sprinting, coinciding with the peak length of the muscle (Higashihara et al., 2015, 2018). This dynamic is thought to represent the mechanism of hamstring strain injury occurrence.

The Nordic hamstring exercise has been demonstrated to significantly reduce first-time hamstring strain injuries by up to 51% (Dyk Van et al., 2019) and recurrent injuries by 86% when included in training programmes demonstrating sufficient athlete compliance (Ekstrand et al., 2022; Petersen et al., 2011).

The relationship between joint angle and muscle length is important as previously injured muscles reach peak torque at significantly shorter lengths (40.9° ± 2.7°) than uninjured muscles of the opposite leg (29.8° ± 1.5°) (Hawkins, 2001).

Gaps in the knowledge:

Limited understanding of the biomechanics of the Nordic hamstring exercise and its relevance to injury risk.

A lack of standardised methods to measure and assess key metrics during the Nordic hamstring exercise.

Current hamstring device limitations and insufficient tools to capture the kinetics, kinematics and muscle activation patterns of the knee flexors concurrently during variations of a Nordic hamstring exercise.

The ability to effectively target the bicep femoris long head muscle at longer muscle lengths (proximally) during the Nordic hamstring exercise before reaching muscle failure (break-point), remains insufficiently understood and inadequately addressed.

Addressed by:

The design and development of a novel device for testing and assessing variations of the Nordic hamstring exercise, guided by a biomechanical design framework grounded in engineering principles.

Research Question:

Can a novel system be developed to effectively modify and measure the relationship between muscle length and torque during variations of the Nordic hamstring exercise to examine hamstring injury risk factors?

Significance:

Scientific contribution: Establishing standardised methods, terminology and metrics to enhance the consistency and comparability of Nordic hamstring exercise research and application.

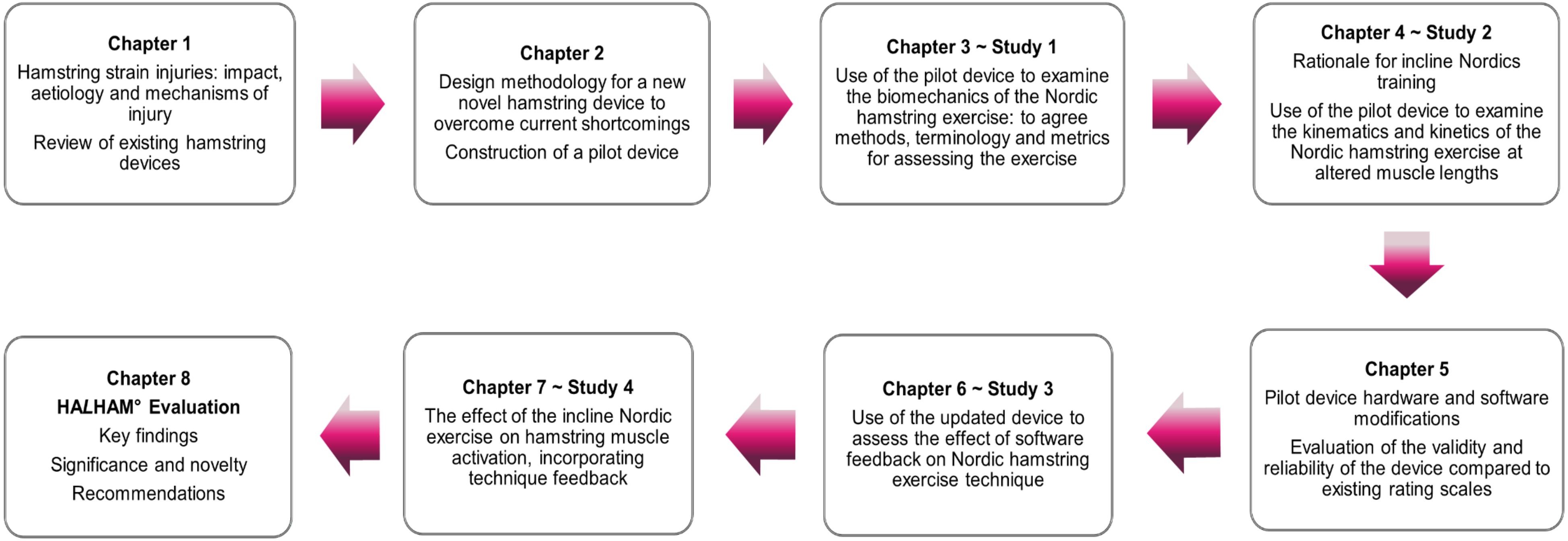
Practical impact: Potential to improve hamstring strain injury prevention and rehabilitation strategies by providing biomechanical insights and evidence-based testing and training protocols.

Device and system innovation: Development of a validated system capable of informing training and rehabilitation practices while being practical and user-friendly.

Originality statement and novelty of the research

The research completed in this thesis represents a novel contribution to the field of sport science and injury prevention through the design, validation and application of the HA*L*HAM° system. The originality of the research lies in its innovative, multidisciplinary approach, combining biomechanics, sports engineering and data analytics to address critical gaps in hamstring strain injury prevention and rehabilitation. To the best of my knowledge and belief, the thesis and the research contained within are original. Due acknowledgement has been provided where reference to existing publications have been made.

Thesis storyboard



Collaborators

The design and production of the HA*L*HAM° was a collaborative effort with the supervisory team; Nick Hamilton and Dr Ben Heller from the Sports Engineering Group (SERG), and Dr Tom Maden-Wilkinson of the Physical Activity, Wellness and Public Health Research Group (PAWPH). All three experts provided invaluable guidance and expertise throughout the research, contributing to design concepts, innovative ideas, frameworks, and technical specifications. This collaboration was instrumental in identifying and implementing solutions to challenges encountered during the research. Nick Hamilton, Director of Studies played a pivotal role in engineering the device (and all its iterations) and further implementing hardware improvements. Dr Ben Heller contributed significantly to the development of the software and the biofeedback system, while Dr Tom Maden-Wilkinson provided valuable insights from his expertise in muscle physiology, providing technical instruction and training on equipment use.

In addition to the collaborative contributions, my personal input involved leading the PhD programme. I conducted an extensive review of existing literature to identify knowledge gaps and establish the research foundation. I was responsible for piloting and testing the HA*L*HAM° system, ensuring the feasibility of the methodology, and identifying key issues that required adjustments. This included troubleshooting technical problems with the equipment and refining the research methods and design. I oversaw data collection both on and off-campus at other institutions and training facilities, managing participant recruitment, obtaining the necessary ethical clearance, and supervising the testing. Additionally, I applied appropriate analytical methods to interpret the data, drawing conclusions and presenting the findings in publications and the thesis.

List of thesis publications

Sconce, E. *et al.* (2024) 'Examining the effect of verbal feedback vs. real-time software feedback on kinetic and kinematic metrics of the Nordic hamstring exercise', *Sport Sciences for Health*. Available at: https://doi.org/10.1007/s11332-024-01294-6.

Sconce, E. *et al.* (2021) 'Development of a novel Nordic hamstring exercise device to measure and modify the knee flexors' torque-length relationship', *Frontiers in Sports and Active Living*, 3(629606), pp. 1-9. Available at: https://doi.org/10.3389/fspor.2021.629606.

Sconce, E. *et al.* (2021) 'Agreement between methods and terminology used to assess the kinematics of the Nordic hamstring exercise', *Journal of Sports Sciences,* 39(24), pp. 2859-2868. Available at: https://doi.org/10.1080/02640414.2021.1968127.

Acknowledgements

Firstly, I would like to thank my director of studies, Nick Hamilton, and supervisory team of Dr Ben Heller and Dr Tom Maden-Wilkinson for their continued support, input and invaluable contributions throughout the past seven years. Nick, I am incredibly grateful to you for allowing me the initial opportunity to pursue this research through the Vice chancellor's scholarship, especially through my 'rabbit in the headlights' moments. Thank you for working with me to build the device, and for constantly challenging me to think outside the box, build my confidence, and persevere, even in the difficult times. I have truly loved brainstorming and discussing ideas with you, even when most of them were less than great on my part! Beyond the academic insights, your mentorship has made me a more resilient and determined person. Ben, thank you for your expert guidance (and patience) in developing the HA*L*HAM° software and spending the time to help me understand the technicalities of the feedback system and data processing in MATLAB. Tom, thank you for training me in ultrasound techniques, and for your humour throughout. Your expertise in muscle physiology and help with data collection has been essential to the success of the studies. I have massively enjoyed the highly collaborative, growth-orientated nature of the process. The regular group meetings, including all 84 monthly meetings, and the numerous one-on-one discussions have pushed me to think critically and strive for excellence in my research. Your high expectations and constructive feedback have motivated me to step out of my comfort zone, ultimately leading to academic and professional levels I thought beyond my reach.

I would also like to thank all the participants in the research studies, particularly the students and staff at the Sheffield Hallam University campuses, and the Lancaster University women's football teams. I am grateful to the laboratory staff, Katie and Brent for their assistance with lab bookings, and ensuring the smooth operation of the equipment. A special thanks goes to football captains, Annabelle and Laura, as well as my friends Natalie, Louise and Jodie for their efforts and support during the pilot testing and data collection. Their endless help in moving and unloading equipment, testing various devices during the pilot stages, and consistently being pillars of strength over the years (even when my free time was limited), has ensured I have reached the finish line. Thank you to all my football coaching colleagues and players for their continued encouragement and inspiration on a daily basis.

Finally, a huge mention goes to family, whose unwavering support and love have made this journey possible. To Pauline and David, thank you for your incredible help from crafting test equipment, to sewing landing cushions, and for always being shoulders to lean on. To Claire, Mark, Archie, Edi and Besty, thank you for providing much needed joy and laughter, and a distraction through tough times. To Malcolm and Alfred thank you for always managing to pull me away from work with your delightful Cavalier King Charles antics and reminding me of how simple life should be. Thank you to my beautiful son Leo for coming into my life and being the light in every day.

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Nomenclature

ANHEQ – Assessing Nordic hamstring exercise quality

AVK – Angular velocity of the knee joint

BF – Bicep femoris

BF_{LH} – Bicep femoris long head

BLD – Bilateral limb difference

BPA – Break point angle

BTA – Break torque angle

CAD – Computer-aided-design

COM - Centre of mass

CV – Coefficient of variation

DEC – Decline slope

DWA – Downward acceleration

EMG – Electromyography

F_g – Force applied by gravity

F_L – Force applied through the load cells

F_{left} – Force from the left limb

fMRI – Functional magnetic resonance imaging

F_{peak} – Peak force (maximum bilateral force)

F_{right} – Force from the right limb

F_S – Force applied through ankle resistance

HF_{max} – Maximum hip flexion

HSI – Hamstring strain injury

ICC – Intraclass correlation coefficients

iEMG – Integrated electromyography

IMU – Inertial measurement unit

INC – Incline slope

IQR – Interquartile range

KEA – Knee extension angle

L-M ratio – Lateral-to-medial hamstring ratio

l_{shank} - shank length

Mean ω_{KE} – Mean knee extension velocity

MDC – Minimal detectable change

MVC – Maximal voluntary contraction

NHE – Nordic hamstring exercise

pVelocity – peak knee angular velocity

r – moment arm length

ROM – Range of motion

ROM_{DWA} – Range of motion to downward acceleration in relation to range of motion of the knee joint

ROM_{hip} – Range of motion of the hip joint

ROM_{knee} – Range of motion of the knee joint

RoR – Rate of Rise

RTA – Relative trunk-to-thigh angle

RThighBA – Relative thigh break angle

RTrunkBA – Relative trunk break angle

SD – Standard deviation

SEM – Standard error of measurement

sEMG – Surface electromyography

SM – Semimembranosus

ST – Semitendinosus

T*ke* – Torque produced by the knee extensors

T*kf* – Torque produced by the knee flexors

$\mathbf{t}_{NHE}$ – Time under tension during Nordic hamstring exercise

$\boldsymbol{T}_{norm}$ – Peak torque normalised to body mass

$\boldsymbol{T}_{peak}$ – Peak torque

x – Perpendicular distance to COM

θ – Angle of theta

$\boldsymbol{\theta}_{knee}$ – Knee joint angle

$\boldsymbol{\theta}_{thigh}$ – Thigh segment angle

$\boldsymbol{\theta}_{trunk}$ – Trunk segment angle

Chapter One

Hamstring Strain Injuries in Sport:

Current Evidence, Knowledge Gaps, and Device Limitations.

This chapter examines the current prevalence of hamstring strain injuries (HSI), their known proposed mechanisms of injury, and the modifiable risk factors contributing to their occurrence. It reviews the current approaches for HSI prevention, associated rehabilitation exercise strategies and the limitations of existing hamstring devices utilising the Nordic hamstring exercise (NHE). Collectively, this chapter highlights the gaps in current knowledge whilst providing a rationale for the overarching aims of the thesis.

1.1 Chapter aim

The aim of this chapter was to discuss the epidemiology, mechanisms and modifiable risk factors of HSIs, providing the rationale for the development of a novel assessment device.

1.1.1 Chapter objectives

i. Review the epidemiology of HSIs, including incidence, severity and associated costs.

ii. Discuss the current theoretical mechanisms of HSIs.

iii. Describe HSI modifiable risk factors that can be tested and trained using hamstring devices.

iv. Compare the validity of existing hamstring testing and training devices, detailing their strengths and limitations.

v. Establish the rationale for measuring the torque-length relationship of the knee flexors during the NHE.

1.2 Literature Review

HSIs pose a major challenge in sports where maintaining peak performance levels and ensuring athletes remain injury-free is paramount for success. A missed mean playing time of 14 competition days per injury (Ekstrand et al., 2011) can result in substantial financial strain (Ekstrand et al., 2013) and have a detrimental impact on a team’s performance (Woods et al., 2004). Therefore, being able to identify players at risk of a HSI and prevent muscle injury is of high value to elite sports. This literature review highlights the epidemiology and mechanisms of HSIs, their impact on athletes, and the limitations of existing assessment devices, thereby establishing the need for more effective methods of hamstring assessment.

1.3 Epidemiology of hamstring strain injuries

1.3.2 Incidence and prevalence

Muscle strain injuries contribute to 10-55% of all sports-related injuries, primarily affecting field-based sports such as football, rugby union, American football, field hockey, Gaelic football, hurling and Australian Rules football (Fuller et al., 2020; Maniar et al., 2023), imposing a substantial burden on athletes. Among these, HSIs are one of the prevalent non-contact injuries in sport, particularly in high-speed running disciplines. HSIs are common lower limb injuries that occur in intensive, acyclic sports (Ekstrand et al., 2011; Maniar et al., 2023) exhibiting an 18% re-injury rate, worsened by the poor-quality formation of scar tissue in the myotendinous junction post-injury (Hägglund et al., 2006). A systematic review and meta-analysis by Maniar et al., (2023) analysing 63 articles and 5952 injuries, reported that the incidence of HSIs was 0.81 per 100 hours, with no significant difference across sports (p=0.593), showing a stable trend over the past 30 years up to 2021 (p=0.269). This highlights the continued need to address this persistent issue and reduce the incidence of HSIs, especially in field-based sports.

HSI prevalence varies by sport, position, and playing level, however they are far more common in activities involving sprinting and high intensity running, where it is reported that HSIs specifically account for 12-29% of all injuries and more than a third of all strains (Brooks et al., 2006; Ekstrand et al., 2011, 2012). These types of injuries normally occur acutely (70%) and in non-contact situations (96%) (Ekstrand et al., 2011), primarily affecting the biceps femoris long-head (BF_{LH}) muscle and typically occur at the proximal musculotendinous junction (De Smet and Best, 2000; Woodley and Mercer, 2005; Ekstrand et al., 2012; Cross et al., 2013).

In elite football, HSIs account for 12% of total injuries over 2 seasons, with a typical 25 player squad experiencing 5-7 HSIs each season (Ekstrand et al., 2011, 2016, 2022). Despite a rise in research interest and implementation, the incidence of HSIs in men's football continues to rise annually by approximately 4% per year (Ekstrand et al., 2016). The proportion of injuries diagnosed as hamstring injuries doubled from 12% in 2001/02 to 24% in the 2021/22 season (Ekstrand et al., 2023). The latest and most extensive club injury epidemiology study by UEFA, on women's elite clubs (n=596 players) from several countries (15 elite teams in Europe) across several seasons (44 team seasons) reports that teams can anticipate 35-time loss injuries per season (1.5 injuries per player). Furthermore, HSIs accounted for 12% of the most frequent injuries, translating to 188 HSIs out of 1527 overall recorded injuries in 463 players. These findings reinforce the ongoing prevalence of lower-limb muscle strain injuries in elite sport and the distinct challenges they pose. While HSIs cannot be predicted with certainty (Van Dyk et al., 2017), given their prevalence, the prevention of initial injury becomes critical (Orchard & Seward, 2002; Visser et al., 2012; Woods et al., 2004).

1.3.3 Severity and economic burden

Severity is often characterised by significant time-loss, with athletes sidelined for an average of 17 days per injury. Grade I injuries result in a time loss of 17 ± 10 days, Grade II injuries 22 ± 11 days and Grade III injuries 73 ± 60 days (wide variability) (Mueller-Wolfhart et al., 2013). Re-injury rates are marked by frequent reoccurrence, ranging from 14-63% within 2 years depending on the sport, competition levels, and rehabilitation quality (Ekstrand, 2013; Ekstrand et al., 2004, 2023; Fuller et al., 2020; Maniar et al., 2023; Visser et al., 2012). Beyond the immediate time loss, recurrent HSIs are often associated with long-term strength deficits, altered neuromuscular function, reduced performance capacity, and increased risk of future musculoskeletal complications (Bourne et al., 2015; Fyfe et al., 2013; Opar et al., 2012; Timmins, Bourne, et al., 2016).

HSIs in football are extensively reported in the sports injury literature, largely due to their significant financial impact on clubs and the considerable time-loss burden they impose on players. Eliakim et al., (2020) estimate that a football English Premier League team loses an average of £45 million per season due to injury burden (£36 million based on underachievement and £9 million being the cost of an injured player’s salary). Torrejón et al., (2024) reported that in the 2018/2019 season, HSIs cost football clubs in the La Liga professional first division an average €47,388 per month. The high cost of HSIs justifies the need for continued research. HSI football rehabilitation is time-dependent based on severity however it can be extensive, up to 90 days (Erickson & Sherry, 2017). On average, the time lost per player is 18 days (increased to 21.5 days of absence when there is a re-injury) and 3 matches missed, equivalent to around 108 cumulative days lost and 18 missed matches per team, per season (Bengtsson et al., 2018; Ekstrand et al., 2011).

Key insight*:* Despite decades of inquiry into risk factors and causation, the persistently high injury rates necessitate further investigation.

1.4 Hamstring muscle group

The hamstrings are a term for a collective muscle group located in the posterior compartment of the thighs, consisting of 3 bi-articular muscles; the biceps femoris (BF) consisting of the longus capitis and longus brevis, the semitendinosus (ST) and the semimembranosus (SM). The BF captum longum and the ST form the long head of the two-headed hamstring thigh muscle and are located in the surface layer. The BF caput breve and the SM form the short head and are positioned in the deep layer (Ivan, 2012). The two-headed muscle fibres of the hamstring are orientated downward and laterally. Proximally, the SM, ST, and bicep femoris long head (BF_{LH}) insert at the ischial tuberosity, extending posteriorly to the knee and hip joints, whilst the BF short-head is monoarticular crossing only the knee joint (Ahmad et al., 2013; Woodley & Mercer, 2005). Given its susceptibility to injury during sporting movements, particularly running, sprinting, and kicking (Cross et al., 2013), the BF_{LH} stands out as a muscle of particular interest in HSI research. HSIs primarily affect the BF_{LH} muscle, with 70-83% of cases localised to the proximal musculotendinous junction (Askling et al., 2007; Grange et al., 2023; Hallén & Ekstrand, 2014). This region is vulnerable due to the high mechanical demands placed on it during activities such as high-speed running. The proximal musculotendinous junction is where peak forces are generated as the BF_{LH} rapidly lengthens under load, contributing to the high injury incidence in this location.

Key insight*:* The BF_{LH} muscle is the most commonly injured muscle in the hamstring complex during high-intensity movements.

1.5 Hamstring injury mechanism

1.5.1 Late-swing phase of sprinting

The occurrence of HSIs is associated with the hamstrings being subject to high forces during rapid muscle lengthening actions (muscle-tendon stretch and negative work), such as in high-speed running (Opar et al., 2012). The hamstrings influence the movement of the hip (extension) and knee (flexion) in the gait cycle in conjunction with the quadriceps acting as an antagonist (Beltran et al., 2012; Ivan, 2012). During the late swing phase, the hamstrings rapidly change from acting eccentrically (decelerating the extended knee) to concentrically (supporting hip extension). This places them in a more susceptible extended position under high mechanical stress, as the hamstrings develop maximal tension to stabilise the knee joint (Guex et al., 2012a). This simultaneous action at both joints places the muscle-tendon unit under substantial strain with hamstring musculature being subjected to large net peak eccentric muscle forces of up to 5200N (Chumanov et al., 2007, 2012; McIntyre, 2022).

1.5.1 Bicep femoris long head

The BF_{LH} experiences the greatest musculotendon stretch during sprinting, potentially contributing to its tendency to be injured more often than the SM and ST (Askling et al., 2007). Biomechanical modelling studies have shown that peak hamstring length and force occur just before foot strike, especially in the BF_{LH}, making it particularly vulnerable to strain (Chumanov et al., 2007, 2011, 2012; Heiderscheit et al., 2005). During the late swing phase, the BF_{LH} needs to tolerate forces ranging between 10.5-26.4N.Kg^{-1} (Claire. Kenneally-Dabrowski et al., 2019), while lengthening up to 110% of its resting length (Thelen et al., 2005). This combination of high force and extreme length and stretch changes is considered a key contributing factor in the mechanism underlying HSIs. Furthermore, electromyography (EMG) analyses have reported increased neuromuscular activation during this phase, and the peak musculotendon length was synchronous with the peak EMG activation in the BF_{LH} muscle (Higashihara et al., 2016). This combination of high eccentric load, extended muscle length and rapid force development underlines a key mechanistic vulnerability that contributes to HSI risk. The hamstrings' role as both agonist and antagonist in the gait cycle also demands rapid transitions between muscle actions (eccentric to concentric), further compounding their susceptibility to strain injuries (Guex et al., 2012b). This interplay of muscle actions during the gait cycle highlights when the hamstrings are particularly susceptible to injury, and the biomechanics contributing to HSI occurrence.

Key insight: BF_{LH} muscle activity peaks during the late-swing phase of sprinting, coinciding with the peak length of the muscle, and reflecting the point at which HSI is likely to occur.

1.5.2 Biceps femoris and semitendinosus relationship

Higher levels of muscle activation are generally favourable for resisting strain, attributed to a higher Young's modulus and increased stiffness. Bourne et al. (2016) assessed muscle activation patterns in the NHE using functional magnetic resonance imaging (fMRI). They reported that the ST, the long and thin, fusiform muscle is preferentially activated during the NHE than any of the other hamstring muscles. Mendiguchia, Alentorn-Geli, et al. (2013), also employed fMRI to investigate the NHE, reporting similar findings, observing a greater percentage change in T2 relaxation time for the ST (14-20%) than for the BF_{LH} (6-7%). T2 relaxation time is an MRI-derived parameter that reflects changes in water content and muscle activation; an increase in T2 is typically interpreted as an indirect marker of muscle recruitment and metabolic activity following exercise (Mendiguchia, Arcos, et al., 2013; Schuermans et al., 2014). Therefore, a greater T2 shift in the ST suggests it may be more activated during the NHE compared to the BF_{LH}.

Interestingly, another fMRI study by Schuermans et al., (2014) suggested that poor or altered muscle activation patterns between the BF_{LH} and ST may be a precursor to an increased risk of HSI. The ST has a reduced ability to generate tension and is more prone to the onset of fatigue. When the ST struggles to sustain force production during negative work (eccentric contraction) this can lead to the BF_{LH} partly compensating for the lack of endurance capacity of the ST (Higashihara et al., 2016; Hirose et al., 2021). The less stretch tolerant BF_{LH} is not suited to being able to control the hip and knee torques in its proximal range of motion, which is crucial in controlling stretch in the late swing phase (Chumanov et al., 2007, 2011; Heiderscheit et al., 2005; Schuermans et al., 2014).

Key insight: The BF_{LH}-ST muscle activation relationship has implications for injury risk and mechanism.

1.5.3 Eccentric vs. isometric action during the late swing phase

It is widely assumed that the hamstrings undergo an eccentric action during the late swing phase of high-speed running, however, some studies have challenged this assumption (Van Hooren & Bosch, 2016, 2017, 2018). During the late swing phase, the distance between musculotendinous attachment points is increased and they move apart. This increase has commonly been assumed as the lengthening of the muscle-tendon unit, however, Van Hooren and Bosch, (2017) argue that the contractile element of the muscle (fascicles) and series elastic element (tendon, aponeurosis and connective tissue) can act differentially and that the lengthening of the muscle-tendon unit does not necessarily mean the fascicles are lengthening. Instead, they hypothesise that the fascicles could be shortening or providing a quasi-isometric action, while the series elastic element recoils as the knee extends, causing the leg to forcefully retract prior to ground contact. An eccentric action may still be the cause of a HSI, possibly as a result of the fascicle's inability to remain isometric, resulting from a lack of control of muscle slack at high forces (the delay between the start of the contractile element contraction and the series elastic element recoil) with concomitant exposure to injury (Ishikawa et al., 2005; Sousa et al., 2007; Van Hooren & Bosch, 2017).

Furthermore, Van Hooren & Bosch, (2017) recommend that high-intensity isometric exercises might be equally or even more effective than eccentric training for hamstring conditioning However, this perspective is disputed by Shield and Murphy (2018), who argue that current biomechanical models indicate hamstring fascicles actively lengthen during the late swing phase (Chumanov et al., 2007) and that strain injury is unlikely to occur during isometric contractions (Lieber & Fridén, 2002). They propose that only eccentric actions can induce sufficient muscle damage at moderate lengths to subsequently evoke the required architectural adaptations needed to create damage resistance (Shield & Murphy, 2018). The NHE is considered a supramaximal load exercise, in which the participant continues resisting the forward-falling motion until reaching eccentric muscle *failure,* at which point they can no longer control the descent and fall forward (Sconce et al., 2015).

Key insight: Supramaximal eccentric contractions actions, rather than isometric, are more likely to produce the muscular adaptations necessary for HSI prevention.

1.6 Nordic hamstring exercise training

The NHE is the most widely researched eccentric training exercise and NHE strength training has been proposed as a method to prevent HSIs (Arnason et al., 2008; Askling et al., 2003; Croisier, 2004; Nunes et al., 2024; Van Der Horst et al., 2015). It has attracted much interest in the literature due to its success in reducing first-time HSI by up to 51% (Nunes et al., 2024; Van Dyk et al., 2019) and recurrent injuries by 86% (Petersen et al., 2011) when included in prevention programmes demonstrating sufficient athlete compliance (Arnason et al., 2008; Petersen et al., 2011; Ripley et al., 2021a; Van Der Horst et al., 2015). An umbrella review by Nunes et al., (2024) found that across 10 systematic reviews assessed with AMSTAR-2 (a valid tool for appraising the methodological quality of systematic reviews) and encompassing over 17,000 participants, NHE interventions consistently improved sprint performance, eccentric strength, and muscle architecture, while reducing injury incidence by half. Moreover, a statement paper by Ishøi et al., (2020) observed a moderate quality of evidence and a medium to large HSI preventative effect size for interventions including both the NHE (Dyk Van et al., 2019) and the FIFA 11+ intervention. Furthermore, an isolated 10-week NHE protocol demonstrated high quality of evidence and a large effect size for prevention (Petersen et al., 2011; Van Der Horst et al., 2015).

This raises a critical discussion point whether the observed reductions in hamstring injury risk are attributable to the unique biomechanical and neuromuscular demands of the NHE itself, or whether they are instead a byproduct of athletes engaging more consistently in general strength and conditioning programmes. While the NHE offers a highly specific stimulus, targeting eccentric strength and replicating the demands of the late swing phase of sprinting, taking part in regular structured strength and conditioning may independently enhance injury resilience. Some researchers argue that the protective effect of the NHE could be a partial reflection of the broader benefits of well-structured and compliant training programmes where consistent monitoring and progression contribute to reduced injury risk (Impellizzeri et al., 2021; Shield & Bourne, 2018; Turner et al., 2013). However, controlled studies that have isolated the NHE within multicomponent interventions continue to report significant effects, suggesting that the NHE provides adaptations beyond those attributable to general training intervention compliance (Arnason et al., 2008; Bahr et al., 2015; Seymore et al., 2017; Van Dyk et al., 2019). Moreover, the NHE has been shown to elicit specific physiological adaptations such as increased eccentric strength and fascicle length of the BF_{LH} (Timmins, Bourne, et al., 2016), both of which are strongly associated with reduced susceptibility to HSIs.

Therefore, while athlete compliance and a targeted strength and conditioning programme remains a critical factor in the success of any injury prevention strategy, the distinct mechanistic contribution of the NHE warrants separate recognition. This distinction is important to clarify, particularly in evaluating the relative effectiveness of targeted interventions like the NHE within broader injury prevention frameworks.

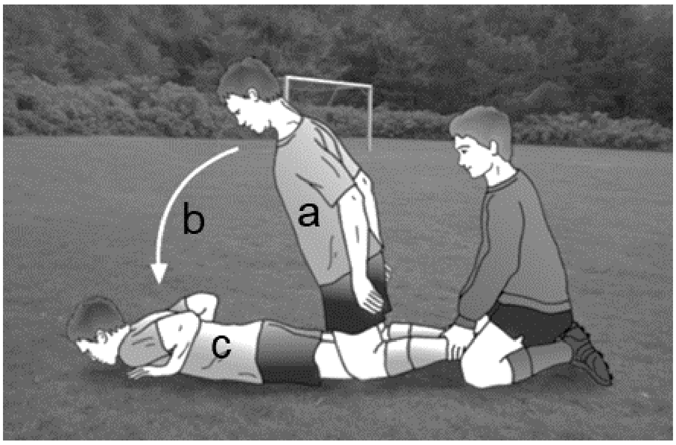


Figure 1**:** Nordic hamstring exercise: (a) starting position, (b) mid-point and (c) end position. Image replicated from Petersen et al. (2011).

The NHE is an eccentric-only exercise (**Figure 1**), placing load on the hamstring muscles whilst they are lengthening (Presland et al., 2018; Timmins, Shield, et al., 2016). During the NHE, gravity elicits the forward fall of the trunk. As the forward lean of the trunk increases, the magnitude of the moment (rotational component) of gravity around the knee becomes greater. In contrast, the contraction of the knee flexors opposes the movement (Ditroilo et al., 2013). The NHE has been shown to provide positive strength and anatomical adaptations in the knee flexors (Presland et al., 2018; Timmins, Ruddy, et al., 2016), however the mechanism of this effect is still unclear and conflicting in the research. Some researchers attribute muscle architecture changes to more sarcomeres in series following eccentric bouts of training leading to a more effective series compliance of the muscle (Brockett et al., 2001, 2004). The slow, eccentric, and maximal nature of the NHE (knee flexors are overloaded past their capacity) appears to result in a true eccentric mechanism that provides a stimulus whereby the myosin heads are already attached to actin and forced to detach by the lengthening of the cross-bridges incurring muscle damage (Cuthbert et al., 2020a; Franchi et al., 2017). The driver of the adaptations observed through NHE training is likely to be as a result of time under tension (Cuthbert et al., 2020b) as studies using load interventions i.e. when athletes can control velocity through the full range of motion, show greater adaptations (Pollard et al., 2019; Presland et al., 2018; Ruddy et al., 2018).

Bourne, Duhig, et al., (2017) and Bourne, Williams, et al., (2017) reported that hip extension exercises selectively target the BF_{LH}, while the NHE selectively recruits the ST. The T2 increase was notably greater for the ST compared to other hamstring muscles (mean diff=16.2-29.9%, $p \leq 0.002$), indicating elevated metabolic activity in the response to the NHE. While increased BF_{LH} muscle activation during the eccentric phase of the NHE compared to other exercises (71.9%) confirms recruitment patterns (Bourne, Williams, et al., 2017), this alone does not constitute evidence of a protective effect. However, when considered alongside longitudinal findings showing that the NHE increases both fascicle length and eccentric strength in the BF_{LH} (Timmins, Bourne, et al., 2016; Timmins, Shield, et al., 2016), these recruitment patterns support a plausible mechanism for injury prevention. Therefore, the combination of targeted high muscle activation, supramaximal eccentric loading, and specific architectural adaptations provides converging evidence for the protective role of the NHE in HSI reduction, beyond just muscle activation alone (Bourne, Duhig, et al., 2017; Timmins, Bourne, et al., 2016; Timmins, Ruddy, et al., 2016; Timmins, Shield, et al., 2016).

Ekstrand et al. (2022) is the most recent study to compare HSI rates among European male football teams. Players using the NHE in their team training had fewer HSIs (5 vs. 11 per team across a season), less severe injuries, lower recurrence rates, and an overall lower injury burden (12 vs. 35 lay-off days per 1000 hours, $p=0.003$) when compared to teams exclusively implementing the NHE only for players with a history of, or current HSI. Despite the substantial body of evidence supporting the effectiveness of NHE training in reducing HSIs, a critical challenge is the low adoption rate seen across European football teams which reported very low compliance at only 13% in the 2020/2021 season. The primary complaints related to muscle stiffness or soreness post-training sessions (Ekstrand et al., 2022). This highlights the need for further investigation and the development of strategies to improve NHE adoption, potentially through technology or innovative design. Addressing these challenges could lead to lowering the injury burden that teams continue to face.

Key insight: When the NHE has been implemented in studies with adequate compliance, it has been associated with a significant reduction in HSI incidence.

1.7 Hamstring strain injury risk factors

HSI risk factors have been extensively documented in the literature across a multitude of sports (Bourne et al., 2015; Foreman et al., 2006; Gabbe et al., 2006; Green et al., 2020; Opar et al., 2015; Verrall, 2001) and are typically categorised as either modifiable or non-modifiable. Non-modifiable risk factors include age, ethnicity, anatomical muscle composition, and previous injury (Green et al., 2020; Opar et al., 2012) whereas modifiable risk factors (those that can be influenced by training) include an insufficient warm-up, fatigue, poor lumbar posture, lack of muscle flexibility or mobility, increased neural tension and muscle architectural properties such as strength (both low force production and a greater limb imbalance). However, it is documented that the theoretical foundation and results from several clinical studies on some of these risk factors are inconsistent (Liu et al., 2012).

Given this complexity, and the interaction between risk factors, attributing injury reduction to a single exercise or intervention such as the NHE must be approached with caution. While there is evidence associating NHE implementation with reduced HSI risk, particularly in interventions with high compliance (Petersen et al., 2011; Van Der Horst et al., 2015; Van Dyk et al., 2019), these findings exist within a broader context of confounding variables including training load, player monitoring, recovery strategies and individual injury histories (Beato et al., 2024; Duhig et al., 2019). Further research is required to establish the cause-and-effect relationships between HSIs and proposed modifiable risk factors, to better understand their impact on injury prevention and management. Moreover, the NHE should be considered as one element within a comprehensive, multifactorial injury prevention strategy.

Key insight: Future research on the NHE should aim to increase compliance by targeting modifiable risk factors.

1.7.1 Eccentric strength

High-velocity eccentric loading occurs late in the swing phase of the gait cycle, just prior to heel strike, which has been shown to be the critical point at which hamstring injury occurs (Brockett et al., 2004; Chumanov et al., 2012). Earlier studies focusing on strength have generally been retrospective and contradictory. Orchard et al., (1997) reported that a lower preseason peak concentric hamstring torque correlated with more subsequent HSIs, however a similar, but larger study by Bennell et al. (1998) found no such correlation. Eccentric hamstring strength has traditionally been measured by isokinetic dynamometry and considered the ‘gold standard’ as to which to compare against, however the role of isokinetic strength assessment for detecting the risk of future HSIs is questionable (Green et al., 2018; Van Dyk et al., 2017). This may be in part because it is typically performed in a seated position within a 0-90° knee flexion to extension range. This hip position has low ecological validity and does not permit the hamstrings to be placed in a position which is representative of how injury occurs in sprinting-related activities (Sconce et al., 2015). Moreover, isokinetic testing is expensive and relatively inaccessible outside of research laboratories.

Key insight: Traditional isokinetic testing has limitations in predicting injury risk, emphasising the need for more ecologically valid and biomechanically relevant assessment methods.

1.7.2 Bilateral strength asymmetries

Zakas (2006) proposed that a significantly weaker hamstring compared to the contralateral leg predisposes the weaker hamstring to an elevated risk of injury. A standard NHE stresses both limbs and through targeted training can reduce bilateral strength asymmetries. In elite rugby union, eccentric strength between-limb imbalances of >10% and >15% were associated with a relative risk of 1.4 and 2.4 respectively for future injury (Bourne et al., 2015). However, similar to peak eccentric hamstring strength, the literature has been contradictory regarding bilateral asymmetry. Some researchers have reported that bilateral strength imbalance has no correlation to HSI prediction (Bennell et al., 1998; Yeung et al., 2009), whereas other studies have found that bilateral hamstring strength asymmetry ranging from 8-15% increases the risk of HSI across several sports (Croisier, 2004; Heiser et al., 1984; Orchard et al., 1997; Sugiura et al., 2008).

Key insight: Bilateral hamstring strength asymmetry, particularly imbalance greater than 10% is associated with an increased risk of HSI.

1.7.3 Fascicle length

Several studies have reported increases in fascicle length following eccentric training interventions (Franchi et al., 2017; Potier et al., 2009; Seynnes et al., 2007; Timmins, Bourne, et al., 2016). Muscle fibres have the capacity to increase in diameter and in length. Muscle fibres that increase in diameter have more structural units (sarcomeres) in parallel in the muscle myofibrils, which determines a higher force orientation. When fibres increase in length this results in an increase in the number of sarcomeres in series, which determines a high velocity and range of motion (Brockett et al., 2001; Goldspink, 1985; Timmins, Bourne, et al., 2016). It has been proposed in the literature that the inclusion of additional risk factors such as BF_{LH} fascicle length may enhance HSI predictive ability (Ruddy et al., 2018). Bourne, Williams, et al., (2017) reported that compared to hip extension (HE) exercises the NHE elicited greater BF_{LH} fascicle length changes over 10 weeks of training (NHE post-training mean difference=2.22 cm, 1.74 to 2.69cm, $p<0.001$, $d=2.17$; HE post-training mean difference=1.33cm, 0.86 to 1.80cm, $p<0.001$, $d=1.77$). This finding is particularly relevant for preferentially choosing the NHE in injury prevention programmes, and moreover, Timmins, Bourne, Shield, Williams, et al., (2016) reported that for every 5mm increase in fascicle length, HSI risk reduced by 75%. Furthermore, soccer players with both short BF_{LH} fascicle length (<10.56cm) and low eccentric hamstring strength (<337N) were 4.4 x more likely to suffer a HSI than those with just longer fascicles *or* higher levels of strength (Green et al., 2018; Timmins, Bourne, et al., 2016).

It should be noted that the literature is conflicting with some studies reporting fascicle length increases of between 16-34% in response to 5-10 weeks of eccentric training (Alonso-Fernandez et al., 2018; Bourne, Williams, et al., 2017; Pollard et al., 2019; Potier et al., 2009) whereas Seymore et al., (2017) reported no such changes in fascicle length after 6 weeks of training. However, this may have been due to the relatively short muscle lengths experienced with the standard NHE training protocol in this study, especially when used in combination with high volume (Guex et al., 2016). In Ditroilo et al. (2013) the mean angle at which participants were actively eccentrically resisting the movement during a standard NHE, was 68.1° ± 8.0° (with 90° representing the kneeling start position). Beyond this angle, participants were no longer able to control the descent, and the remainder of the motion was largely passive, meaning that most participants utilised less than a third of the available range of motion. This limited eccentric control is likely to be further exacerbated in recreational participants, potentially accounting for the discrepancies reported by Seymore et al., (2017) considering their use of a recreational cohort, who typically exhibit lower levels of eccentric strength, motor control and training experience compared to elite athletes (Gabbe et al., 2006; Koller et al., 2015).

Moreover, a recent systematic review and meta-analyses by Cuthbert et al. (2020b) showed that NHE interventions of $\geq$6 weeks reported very large positive effect sizes for changes in fascicle length ($g \geq 2.58$) with moderate to high consistency reported for muscle architecture (I^2 =88.03%). In a study by Presland et al., (2018) BF_{LH} fascicle length increased significantly in males (24 ± 4%, $p<0.001$, $d=3.46$) following a NHE 6-week training programme but reversed following 2 weeks of detraining (-15 ± 3%, $p<0.001$, $d=-2.56$) whereas eccentric strength significantly increased (34 ± 14%, $p<0.001$, $d=2.09$) and was maintained following 4 weeks of detraining (-2 ± 5%, $p=0.99$, $d=-0.20$). Therefore, consistent, and regular eccentric training is required to maintain the beneficial adaptation of increased fascicle length which should be a consideration when planning training protocols. Longer fascicles, with more sarcomeres in series may be less susceptible to being overstretched and more resistant to damage from forceful eccentric actions (Brockett et al., 2001; Timmins, Shield, Williams, Lorenzen, et al., 2016). Athletes should strive to increase their ability to withstand larger amounts of strain, through increasing the length and maximal elongation capacities of the structures subject to length changes in the musculotendinous unit, such as fascicles (Kalkhoven & Watsford, 2020).

Key insight: Monitoring *both* eccentric hamstring strength and fascicle length is important when devising targeted hamstring testing and training strategies.

1.8 Training at longer muscle lengths

With the mechanism behind why the NHE is so beneficial being unclear, Seymore et al., (2017) suggested its effectiveness could be attributed to increasing muscle volume rather than length. This contrasts with findings from other studies with Sharifnezhad et al. (2014) finding that fascicle length increases are dependent on the range of muscle lengths used during the intervention. (Guex et al., 2012b) noted that from a kinematic point of view, the second half of the swing phase extends the knee to less than 40° (Kivi, Maraj and Gervais, 2002; Volpi *et al.*, 2004; Thelen *et al.*, 2005; Schache *et al.*, 2009). Long muscle length chronic training interventions attribute an observed peak torque shift in the direction of longer hamstring muscle lengths to an increase in fascicle length, assumed to reflect more sarcomeres in series and a greater effective series compliance of the muscle (Morgan, 1990; Potier et al., 2009). In eccentric actions where there is a rapid stretch during active muscle-tendon lengthening, it is assumed that longer muscle fibres will exhibit less strain per sarcomere for a given muscle-tendon unit strain and stiffness (Timmins, Shield, et al., 2016).

Research studies employing isometric training at longer muscle lengths have reported greater muscular hypertrophy (5-19.7%) and maximal force production (8-60.3%) in comparison to equal volumes of training at shorter muscle lengths, regardless of training intensity (Oranchuk et al., 2019). Tyler et al. (2017) found that rehabilitating athletes using an eccentric protocol of exercises on isokinetic dynamometry where the hamstrings were intentionally placed in a lengthened, maximally stretched state restored strength [7% were stronger] and resulted in no recurrent injuries at an average of 2 years after their return-to-play. The rehabilitation protocol comprised of 3 distinct training phases progressively advancing athletes from submaximal to maximal contractions. Phase 3 involved isokinetic eccentric contractions in a lengthened state, with participants sitting with the test thigh flexed 40° above the horizontal and the seat back at 90° to the horizontal. Eccentric contractions were performed from 90° to 20° knee flexion at 0.35 rad/s (20°/s). Non-compliant athletes who failed to complete the lengthened eccentric programme returned to play with significantly greater muscle weakness (43% weaker), particularly at long muscle lengths (20°), and experienced a high injury recurrence rate of 50% (Tyler et al., 2017).

Key insight: Training at longer muscle lengths appears to be particularly effective for targeting the BF_{LH} at the typical site of muscle injury.

1.8.1 Break-point angle

A study conducted by Sconce et al., (2015) demonstrated that the NHE break-point angle (BPA) which represents the angle at which an individual can no longer resist the increasing gravitational moment in a NHE and falls to the floor is a valid field-based measure of eccentric hamstring strength (**Figure 2**). Furthermore, this finding has been supported by results in more recent studies including those by Lee et al., (2017, 2018). Notably, Delahunt et al. (2016) reported improvements in kinematic parameters after a 6-week eccentric training programme using the NHE as the sole mode of exercise. The angle at downward acceleration shifted to an optimised longer control of the forward fall component of the NHE (68.1° vs, 73.7°, p=0.022, d=0.90) following the intervention. The angle at downward acceleration can be characterised as being the BPA, representing the end of trunk control due to a sudden increase in velocity, with the angle corresponding to the initial point of the time window that yielded the highest slope difference. The researchers in Delahunt et al. (2016) used a more sophisticated, custom system (Codamotion software) to determine the angle compared with a more basic, visual method used by Sconce et al., (2015) but both methods support the BPA as an important measure of NHE assessment and performance.

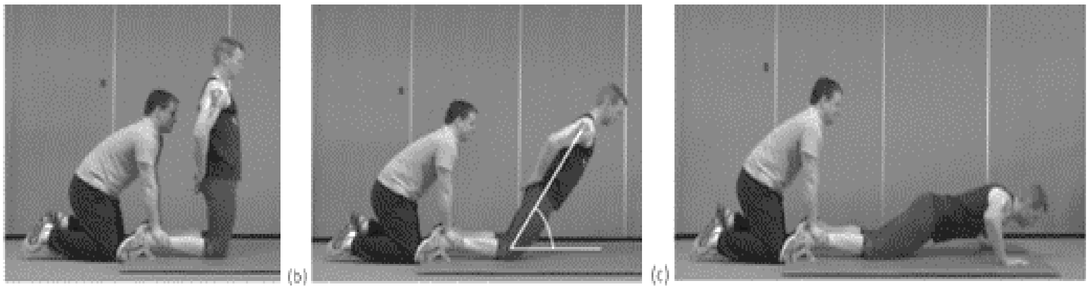


Figure 2: Nordic hamstring exercise: (a) start, (b) midpoint indicating the Nordic break-point angle, and (c) end. Angle is measured from the greater trochanter (hip) to the lateral epicondyle (knee) to the horizontal.

If a NHE action is performed at constant angular velocity, the resisting torque can be considered as equal to the extending torque until the force-production capability of the knee flexors can no longer resist the increasing torque, resulting in the break-point (Sconce et al., 2015). As previously stated, an observed peak torque shift in the direction of more extended angles during long muscle length chronic training interventions is attributed to an increase in fascicle length (Morgan, 1990; Oranchuk et al., 2019; Potier et al., 2009). In the context of the NHE, this could suggest that a larger BPA (where 180° is full extension) corresponds to a longer muscle length at failure (Brughelli & Cronin, 2007), thus potentially leading to greater increases in muscle fascicle length, and consequently modifying the length-tension relationship of the hamstrings, reducing injury risk.

Researchers (Lee et al., 2017, 2018) have developed a smartphone-based method to measure the BPA, termed the ‘CUHK test’ (Lee et al., 2018), reporting a minimal detectable difference of 8.03°. Using a hamstring fatigue repeated sprinting protocol they observed a mean BPA change of 10.06°, signifying that angle could be a potentially meaningful alternative indicator of eccentric hamstring strength changes. It has value as a quick and simple field measurement method; however, it does not account for the torque being produced at specific muscle lengths, which is important for examining the effects of training interventions on any rightward shifts in the length-tension relationship (i.e. a shift towards peak torque occurring at longer muscle lengths) (Guex et al., 2016; Marušič et al., 2020; Šarabon et al., 2019; Tyler et al., 2017).

Key insight: A shift towards angular measurements of the NHE, such as the BPA could be of value in understanding torque-length relationships of the knee flexors.

1.9 Nordic hamstring exercise assessment devices

Portable NHE devices have presented a lower cost alternative to isokinetic dynamometry, offering ongoing monitoring and feedback in an applied setting (Opar et al., 2013; Giacomo et al., 2018; Lodge et al., 2020). In recent research literature, these innovative and reliable devices for measuring eccentric hamstring strength have provided valuable insights into HSI prevention and muscle architecture (Giacomo et al., 2018; Hegyi et al., 2019; McGrath et al., 2020; Presland et al., 2018). While force measurement still remains central to NHE assessment, there has been a rise in the use of kinematic variables to provide a biomechanical analysis of the NHE action (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Lee et al., 2017, 2018; McGrath et al., 2020; Muggleton, 2015; Šarabon et al., 2019; Sconce et al., 2015). The following section of this chapter will discuss the application of testing and metrics in both preventing and rehabilitating HSIs.

Key insight: Several devices currently exist that measure and train knee flexor strength, with each device having its own merits and limitations.

1.9.1 NordBord

The NordBord (**Figure 3**), developed by Opar et al., (2013) employs the NHE to measure eccentric hamstring strength using uniaxial load cells on a fixed board. This method is considered a cost-effective alternative to isokinetic testing, offering both portability and practicality. According to Vald performance (*VALD Performance: NordBord Specification*, 2025), the NordBord is capable of measuring forces up to 2000N, using a default sampling rate of 50Hz (with the option to increase to 400Hz), and employing Bluetooth 5 for wireless communication, enabling real-time data transfer to connected devices. The device weighs approximately 19kg and has dimensions of 120cm (L) x 64cm (W) x 44cm (H), making it highly portable and easy to transport. It has demonstrated excellent test-retest reliability, with intraclass correlation coefficients (ICC) typically reported between 0.83-0.99 for bilateral eccentric knee-flexor force (Claudino et al., 2021; Ogborn et al., 2021). Ogborn et al., (2021) reported ICC=0.993 (95% CI 0.983-0.997) and a minimal detectable change (MDC_{95}) of approximately 27N, while typical standard errors of measurement (SEM) across studies assessing eccentric knee-flexor torque and inter-limb asymmetry range from 6-9% of the mean value (Bourne et al., 2015; Claudino et al., 2021; Opar, Williams, Piatkowski, et al., 2013). These findings align with the established reliability of isokinetic dynamometry which has shown ICC values between 0.90 and 0.97 and SEMs of approximately 4-8% for eccentric and concentric knee-flexor strength measures (Drouin et al., 2004; Feiring et al., 1990). However, differences in testing methods, contraction modes and device configurations have led to variability and conflicting results in reported outcomes across several studies reporting on HSI prevention, NHE training and hamstring rehabilitation (Alt et al., 2022; Bennell et al., 1998; Bourne et al., 2015; Opar, Piatkowski, et al., 2013; Pollard et al., 2019; Van Dyk et al., 2016).

Figure 3: Image of the NordBord hamstring testing device.

NHE training programmes (10 weeks+) have demonstrated large increases (+17-19%) in peak eccentric hamstring strength (Ishøi et al., 2018) and the NordBord has shown an association with lower injury burden. Eccentric hamstring force values below 256N at the start of a men's football preseason indicated a 2.7 x greater risk of subsequent HSI (Bourne et al., 2015; Freckleton & Pizzari, 2013;

Opar et al., 2012; Timmins, Bourne, et al., 2016; Van Dyk et al., 2016). However, a study by Roe et al. (2020) reported no association between eccentric knee flexor strength metrics (values gained from the NordBord) and an increased risk of HSI in elite Gaelic footballers (n=185) across an investigation period of 12 weeks. Twenty-eight players (16%) consequently sustained a time-loss HSI following testing, with the findings recommending that practitioners should avoid managing athletes HSI risk by relying solely on eccentric knee flexor data. Moreover, eccentric hamstring strength values, previous HSI data and age risk factors have not been able to predict athletes at an increased risk of sustaining a HIS (Liu et al., 2012). A more comprehensive and multifactorial approach should be adopted when assessing and managing hamstring risk, with emphasis on considering other contributing factors and not just solely eccentric hamstring strength.

The NordBord device only measures linear force output and not torque about the knee, making measures unrelatable between players of different sizes. Furthermore, it doesn't measure the angular range over which the force can be produced. Such a relationship between joint angle and muscle length is important as previously injured muscles reach peak torque at significantly shorter lengths (40.9° ± 2.7°) than uninjured muscles of the opposite leg (29.8° ± 1.5°) and muscles of both legs in an uninjured group (right=30.1° ± 1.5°, left=17.3° ± 1.2°), where 0° represents full extension (Hawkins, 2001). This emphasises the importance of considering joint angle and muscle length when assessing the NHE. Establishing a consensus on method and device for HSI testing and training would help standardise the research.

Key insight: A device that could modify and measure the torque-length relationship of the knee flexors would be advantageous.

1.9.2 Hamtech

Giacomo et al. (2018) produced a testing device for assessing hamstring muscle function termed the '*Hamtech*' (**Figure 4**). Specifically, the device employs S-type force sensors (capacity ~ 1000N) under each foot and a potentiometer for knee-joint angle, with acquired data at 1000Hz (Giacomo et al., 2018). This device is founded on the theory that hamstring force during lengthening actions is a central component of effective HSI prevention and rehabilitation, similar to the principles proposed by this research (Brughelli & Cronin, 2007; Schmitt et al., 2012; Tyler et al., 2017). The Hamtech claims to alter the force-length relationship in both bilateral and unilateral modalities, allowing progressive work across the spectrum using assistance and resistance protocols by manipulating the hip angle (Giacomo et al., 2018; Hegyi et al., 2019). However, to date, no peer-reviewed study has yet published full test-retest reliability or validity data for the Hamtech, meaning that while the device shows strong conceptual promise, its measurement accuracy and reproducibility have yet to be empirically established.

One of the main advantages of the Hamtech is its capacity to control the knee angle throughout the 90° range of NHE movement whilst manipulating the hip angle to mimic the late swing gait cycle, however this does not allow for a BPA to occur (Hegyi et al., 2019). Moreover, the Hamtech is assisted which doesn't utilise the pure eccentric nature of the NHE, which pertains to be part of why it works so well as an injury prevention exercise (Alt et al., 2021; Giacomo et al., 2018). In resistance training, lifting a weight to muscular failure (the same supramaximal protocol as the NHE) recruits all available motor units using the central nervous system, which is important in building muscle memory and improving neural drive (Gabriel et al., 2006). These are two key aspects of injury rehabilitation exercises and play an important role in muscle strength gains.

As a supramaximal eccentric exercise, it is challenging to maintain constant knee extension velocity and precise hip control throughout the entire range of motion of the descent portion of a NHE (Alt et al., 2020). However, using assisted NHEs to control the full range of motion will remove the supramaximal intensity of the exercise. There is currently little evidence to suggest that assisted NHEs are effective, but more research is required. Cuthbert et al. (2020a) states that there is an argument for providing assistance to allow an increased range of motion in specifically weaker individuals or beginners, as long as a break point occurs ensuring a supramaximal intensity.

Figure 4: Image of the Hamtech testing and training device.

Key insight: A NHE should record a distinct break point to ensure supramaximal intensity occurs. Controlling knee extension velocity and hip control throughout the exercise is challenging, which may impact standardisation of the movement. These factors should be considerations for any hamstring testing device.

1.9.3 Hamstring Solo

The '*Hamstring Solo*' (**Figure 5**) is another commercial hamstring strength testing device, although to the authors knowledge there is no academic research available detailing its development. Similarly, to the NordBord, the Hamstring Solo is portable and utilises the NHE, providing real-time feedback (*elite version*) on various metrics such as eccentric hamstring strength, time to peak force, work done (area under the curve), and bilateral limb asymmetry. It promotes the decline position aspect of its device on its website i.e. the device operates at a NHE decline starting kneeling position, claiming to prevent knee hyperextension and over extension of the knee joint while aiding a more 'comfortable' position. However, this will reduce the knee angle (proxy hamstring length) for any given force output and doesn't reflect eccentric training at a long muscle length which may be important for injury prevention (Tyler et al., 2017).

Device validation work for the Hamstring Solo by Lodge et al., (2020) reported high test-retest reliability for peak eccentric force, with ICC=0.910 (95% CI 0.76-0.96) for the left limb and ICC=0.914 (95% CI 0.78-0.96) for the right limb. The same study reported typical errors (within-session variability) of 14.65N (left) and 17.29 (right), indicating acceptable measurement precision for applied settings (Lodge et al., 2020). In addition, the MDC was calculated to be 40.62N (MDC%=14.68%) and 39.63N (MDC%=13.31%) for the left and right limbs (Lodge et al., 2020). Reliability testing also demonstrated high between-day consistency, with typical errors of 7.2% for the left limb and 8.3% for the right limb, indicating stable performance across sessions (Joshua et al., 2021). Inter-device comparisons also show good agreement with established systems. Ogborn et al., (2021) report that inter-device correlations between comparable Nordic dynamometers, including the Hamstring Solo and the NordBord are moderate to strong (example inter device correlation≈0.82), underscoring broadly comparable measurement performance across commercial devices. Data indicates that the Hamstring Solo provides reliable peak force measures suitable for monitoring eccentric hamstring performance, although device-specific typical errors should be considered when interpreting changes over time or between limbs.

Figure 5: Image of the hamstring solo device.

Key insight: A hamstring training device capable of facilitating eccentric training at longer muscle lengths is recommended for promoting the desired muscular adaptations for injury prevention.

1.10 Device comparison

Comparison **Table 1** highlights the key features of the main NHE testing devices currently available on the market. The comparisons were selected based on the literature review and the metrics hypothesised to be most relevant to HSI prevention and rehabilitation.

Table 1: Comparison table of the main existing hamstring testing devices.

Device	Manufacturer	Primary contraction mode	Kinetic measurement		Concurrent angle measurement	Adjustable inclination mechanism	Real-time kinetic feedback	Data logging software/ app	Portability	Price range
			Force	Torque						
Isokinetic Dynamometry	Various	Eccentric Isometric Concentric	✓	✓	*ROM (Not to measure BPA)*		✓	✓	Low	Between $10000 - $60000
Hand-held dynamometers	Various	Isometric	✓		*ROM*			*Some models have an app*	High	Between £100 - £2000
NordBord	Vald Performance	Eccentric	✓	*Approximated using knee position*			✓	✓	High	Approx $5000 per year
Hamstring Solo	ND Sports Performance	Eccentric	✓	*Approximated using knee position*			✓	✓	High	Elite €5000 w/annual licensing fee of €2500
Hamtech	Human Kinematic	Assisted/Resisted Eccentric Isometric Concentric	✓	✓	*Hip and knee* ✓	*Hip angle can adjust*	✓	✓	Low	€20,000 - 30000
KangaTech KT360	KangaTech	Eccentric Isometric	✓	✓				✓	High	*Not available*

1.10.1 Device choice and metric reporting

With devices such as the NordBord and Hamstring Solo gaining popularity and being adopted by many professional football clubs as a cost-effective and efficient way to measure eccentric hamstring strength, it is important to note that there are equivocal findings that exist on their capacity to test strength and limited evidential research comparing them directly to isokinetic assessment findings (Van Dyk et al., 2018). Addressing this gap, Wiesinger et al. (2020) conducted a critical comparison of the mechanical output of the hamstring muscles assessed by isokinetic dynamometry and a custom-made hamstring device. A controlled test speed and hip position were matched between devices, ensuring that the hamstring muscles could operate under comparable force-length and force-velocity conditions. Measurements taken included eccentric peak torque, work, angle of peak torque, bilateral strength ratios, and the electromyography activity of the BF_{LH}, ST and gastrocnemius. Eccentric peak torque values measured using the Nordic hamstring device and isokinetic dynamometry demonstrated what the authors classified as a *very poor* correlation (left leg: r=0.58, p=0.003; right leg: r=0.51, *p*=0.009) based on their predefined thresholds for correlation magnitude. A proportional and systematic bias was observed towards lower torque values on isokinetic dynamometry (~28%) with a high typical error between devices (~19%) (Wiesinger et al., 2020).

Participants on the isokinetic dynamometry reached peak knee torques at greater knee extension angles, performed a higher total eccentric work, and showed a greater limb-to-limb strength difference compared to the NHE device. Gastrocnemius muscle activity during the NHE was lower, and there was low reliability for work, the angle of peak torque and bilateral knee flexor strength ratios on either device (Wiesinger et al., 2020, 2021). These findings corroborates that each device, even when standardised, reflects different determinants of hamstring muscle strength contraction. Furthermore, different conditions and exercise methods including joint angles, contraction mode, velocity, external load type, force vector and stability on various devices can considerably alter force production, making accurate comparisons challenging.

Key insight: Differences in setup and measurement outputs across current hamstring assessment devices highlight the need for standardisation in future designs to ensure valid and comparable data.

1.11 Rationale

The NHE offers a practical method of hamstring assessment, however, current devices are unable to quantify the torque-length relationship (Delahunt et al., 2016). This limitation is critical, as HSIs are strongly associated with insufficient eccentric strength at extended muscle lengths (Guex et al., 2016; Marušič et al., 2020; Tyler et al., 2017). The final section of this chapter discusses the pertinent torque-length and torque-velocity relationships of the hamstrings to establish the rationale for developing a novel NHE assessment device.

1.11.2 Torque-length relationship

The relationship between maximal torque and muscle length in hamstring function is important for understanding injury mechanisms and assessing the effects of interventions (Kellis & Blazevich, 2022; Marušič et al., 2020). Guex et al. (2012) found that increased hip flexion angle during isokinetic dynamometry, led to higher hamstring peak torque. Moreover, peak hamstrings force remained largely unchanged prior to and immediately following acute sprinting-related injuries, whereas peak hamstrings length was drastically reduced by 40.4%. This suggests that peak torque at the highest elongation of knee flexion is a key determinant of injured muscles (Schache et al., 2010). Pollard et al. (2019) surmised that weighted NHE interventions elicited the greatest muscle architectural changes, including increased eccentric hamstring strength (+81N, $p=0.044$, $d=0.90$) and fascicle length (+1.57cm, $p<0.001$, $d=1.41$). Conversely, only moderate and modest changes were reported for NHE bodyweight training, and razor hamstring curls (90° knee and hip exercise) interventions respectively. These variations are likely attributed due to a greater change in muscle length occurring from the NHE compared to razor hamstring curls, and a higher peak torque elicited from the weighted NHE compared to the conventional body weight version. This suggests that the interplay between muscle length and torque can elicit different responses along the length-tension relationship, resulting in different muscle adaptations.

Current isokinetic dynamometers are limited in their ability to replicate or measure torque at high knee extension angles (145-165°), which correspond to the positions most commonly associated with HSIs (Chumanov et al., 2012; Kenneally-Dabrowski, Brown, et al., 2019). This limitation restricts their capacity to fully assess the torque-length characteristics relevant to injury mechanism. The NHE assessment device needs to overcome this limitation by enabling controlled eccentric testing over a greater angular range, allowing torque to be measured at extended muscle lengths.

Key insight: Precise measurement of both torque and muscle length across the NHE is key for being able to assess adaptive effects. The device must be capable of measuring the critical torque-length relationships at angles not achievable with conventional dynamometry.

1.11.3 Torque-velocity relationship

The torque-velocity relationship describes the inverse association between the speed of muscle contraction and the torque that can be produced (Jaric, 2015). During concentric contractions, maximal torque decreases as contraction velocity increases, whereas during eccentric contractions, torque capacity is maintained or may even increase at higher velocities (Ichihashi et al., 1992; Jaric, 2015; Spendiff et al., 2002). This characteristic is particularly relevant for the hamstrings, as they frequently function eccentrically during high-speed running to decelerate knee extension and hip flexion in the terminal swing phase (Chumanov et al., 2012; Schache et al., 2012). Injury mechanisms are often linked to eccentric action at high angular velocities, where the hamstrings are required to produce torque while lengthening at near-maximal speeds (Chumanov et al., 2007, 2011; Thelen et al., 2005). A reduced capacity to generate eccentric torque eccentric torque at higher velocities has been identified as a potential risk factor for injury (Opar et al., 2012; Timmins, Bourne, et al., 2016).

The NHE is typically performed as slow, bilateral exercise (Cuthbert et al., 2020b). However, this does not replicate the dynamic conditions under which HSIs occur during sprinting, where eccentric hamstring activity takes place at substantially higher angular velocities and under asymmetric loading, within distinct inter-limb differences in activation timing, joint kinetics and coordination patterns (Higashihara et al., 2016, 2018; Higashihara, Nagano, & Takahashi, 2015; Jorge et al., 2024; Schache et al., 2012; Thelen et al., 2005) . Accounting for the torque-velocity relationship during the NHE may therefore provide a more complete assessment of hamstring function than torque-length measures alone. Despite this, current field-based NHE devices are not capable of replicating or capturing torque-velocity relationships at sprint-specific angular velocities (>600°·s^{-1}) (Chumanov et al., 2012; Schache et al., 2012), limiting their ability to fully model the mechanical demands placed on the hamstrings during high-speed running.

When used for hamstring assessment the NHE is usually performed in a controlled manner with relatively slow velocities, to allow for reliable measurement of torque production and technique (Mendiguchia et al., 2020; Van Dyk et al., 2016). Uncontrolled NHE descent speed can bias torque, to be artificially overestimated or underestimated due to the influence of velocity on eccentric force production (Augustsson et al., 2023). Moreover, uncontrolled descent makes it difficult to identify the precise BPA, which represents the transition from controlled eccentric action to failure. Without a clearly defined BPA, the torque-length relationship cannot be accurately quantified (Cuthbert et al., 2020a; Delahunt et al., 2016; Sconce et al., 2015). Therefore, standardising and monitoring NHE velocity during NHE execution is important to ensure valid and comparable measurements between individuals and across trials. It also enables accurate identification of the BPA, thereby allowing the torque-length relationship to be measured consistently.

Key insight*:* Controlling and monitoring NHE velocity is required to obtain an undistorted torque profile and to accurately identify the BPA.

1.12 Chapter conclusion statement

This chapter has examined:

i. **The current prevalence of HSIs** ~ Being able to identify players at risk of a HSI is of high value. More investigation is needed to explore the unexplained continuing high injury rates despite decades of inquiry into risk factors and causation.

ii. **The known mechanism of injury** ~ HSI occurrence is associated with the hamstrings being subject to high forces during rapid muscle lengthening actions in the late-swing phase. This places them in a more susceptible extended position under high mechanical stress.

iii. **Modifiable risk factors** ~ Monitoring both eccentric hamstring strength and fascicle length measurements are important in HSI prediction. New modifiable risk factors, such as the angle of 'break' at peak torque during the NHE, warrant further investigation.

iv. **NHE compliance** ~ More understanding is needed to increase the adoption of NHE training to lower injury burden, possibly through technology or innovative design.

v. **Limitations in current hamstring testing devices** ~ Some devices only measure linear force output and not torque about the knee. Future NHE devices should measure the angle at which peak torque can be produced to provide insight into torque-length characteristics. Developing systems that enable testing and training at longer muscle lengths is desired.

1.13 Aim of the thesis

Based on the findings of the literature, the overarching aim of this thesis is:

To design, validate, and implement a novel hamstring assessment device capable of modifying and measuring the knee flexors' torque-length relationship across NHE inclinations, preferentially targeting the BF_{LH} at longer muscle lengths while maintaining torque production.

1.13.1 Thesis objectives

The objectives of the thesis are organised into four overarching themes:

Device development:

i. Design and develop a novel hamstring assessment device capable of modifying and measuring the relationship between muscle length and torque during the NHE.

ii. Develop and integrate a real-time software biofeedback system to monitor and guide NHE technique.

Standardisation:

iii. Establish standardised methods, terminology and metrics for assessing eccentric hamstring performance and exercise technique quality during the NHE.

Validation:

iv. Determine the validity and reliability of the novel IMU-based HA*L*HAM° system against established gold-standard measurement systems.

Application:

v. Identify the kinetics, kinematics, and muscle activation patterns of performing the NHE at altered muscle lengths.

vi. Compare the effect of software-based biofeedback vs. verbal feedback on NHE performance and technique metrics.

1.13.2 Study hypotheses

Study 1 – Specific angular-torque metrics will provide valid and low-variability indicators of eccentric hamstring performance, rather than relying solely on traditional metrics (e.g. peak torque alone).

Study 2 – Compared to the flat NHE, performing the NHE on an incline will shift the torque-length relationship rightward toward longer muscle lengths, while maintaining comparable torque output.

Pilot study - The IMU-based HA*L*HAM° system will demonstrate acceptable validity and reliability compared to the Polhemus gold standard system. Integration of a biofeedback system is expected to reduce variability in technique and improve measurement reproducibility in future studies.

Study 3 - Using real-time software-based visual biofeedback during the NHE will improve exercise quality by (1) reducing trial-to-trial variability in hip position (RTA at BTA), maintaining values closer to 0° (less hip flexion), and (2) produce a slower and more consistent average descent velocity (AVK) at BTA compared to previous trials without feedback.

Study 4 - The incline NHE will elicit greater BF_{LH} activation at longer muscle lengths compared to the flat NHE.

Chapter 2

Device Design and Development Methodology

This chapter provides a rationale for the specification and design of a novel hamstring assessment device, which aims to build on the strengths of existing hamstring devices, whilst tackling their shortcomings. The chapter begins by summarising the findings of the literature reviewed in **Chapter 1**, serving as the foundation for developing the design principles of a new prototype hamstring device. Important biomechanical relationships pertinent to hamstring injury will be explored and then applied to creating a design specification for a custom dynamometer tailored to meet the specific needs of HSI testing. Finally, given the evidence from **Chapter 1** that the NHE can markedly reduce injury rates when used as part of a compliant training intervention, this chapter discusses the potential of the device to advance assessment and performance, with the aim of redefining the standards for hamstring assessment.

2.1 Chapter aim

The aim of this chapter was to develop a hamstring assessment device capable of modifying and measuring the relationship between muscle length and torque during the NHE.

2.1.1 Chapter objectives

i. Detail the iterative design process and develop a hamstring assessment device capable of modifying and measuring the relationship between muscle length and torque during the NHE.

ii. Outline the methodological considerations for torque and angle measurements during the NHE.

2.2 Introduction

Chapter 1 established that devices assessing hamstring function should consider the torque-length relationship of the hamstrings, which can be achieved by measuring both torque about the knee and the angular range over which the torque can be produced. However, current hamstring devices commonly only measure linear force output, overlooking important biomechanical factors (Opar et al., 2013; Lodge et al., 2020). Current research suggests that having *both* strong and long hamstring muscles is effectual for injury prevention and a faster return-to-play following injury (Bourne et al., 2015; Hegyi et al., 2019; Opar, Piatkowski, et al., 2013; Timmins, Bourne, et al., 2016; Timmins, Shield, et al., 2016). By developing a device capable of targeting the knee flexors at extended lengths, akin to the biomechanics observed during sprinting where the majority of HSIs occur, it is proposed that NHE training can be significantly enhanced in its efficacy for *both* preventing and rehabilitating HSIs (Sconce et al., 2015, 2021a, 2021b).

2.3 Biomechanics of the Nordic hamstring exercise

During the NHE an individual resists knee extension (angle theta) by producing increasing flexion torque (Tkf) about the knee through eccentric action of the knee flexors (**Figure 6**). The torque increase is necessitated by the increasing moment arm (x) around the knee, of a participant's centre of mass (COM), as the person leans forwards.

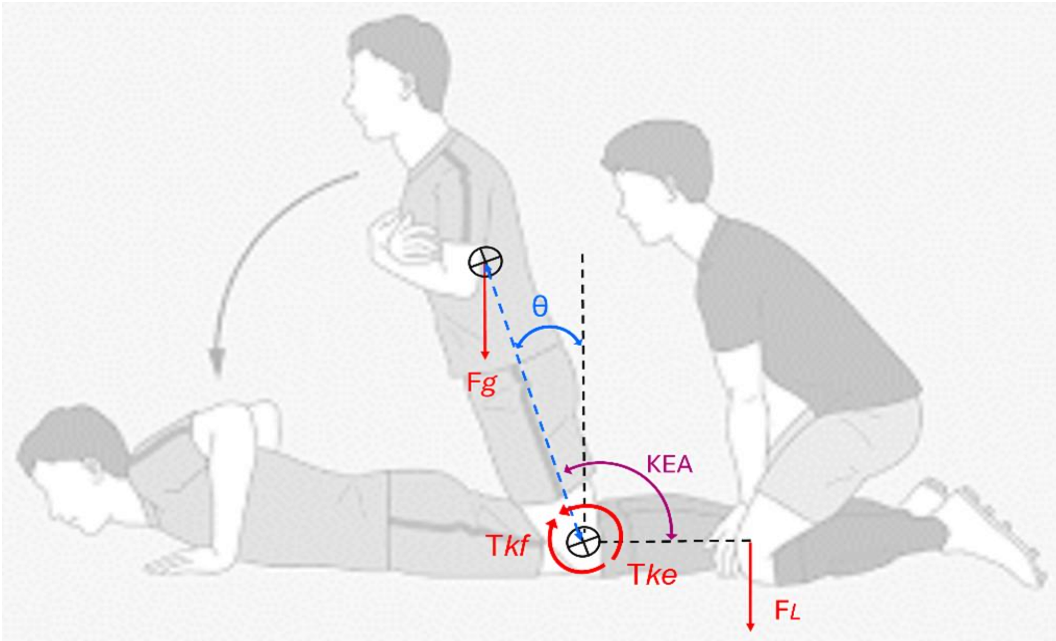


Figure 6: Biomechanical representation of the applied and resisted torques in the Nordic hamstring exercise. F_g weight of thighs and upper body, θ thigh angle to vertical, KEA knee extension angle, T_{kf} torque produced by the knee flexors, T_{ke} torque produced by the knee extensors, F_L force applied through the load cells.

If the motion is at a constant angular velocity, the torque can be considered equal until the force-production capability of the knee flexors can no longer resist the increasing torque, resulting in a 'break-point' where the participant falls forward to the ground. At a slow and constant speed, the forces and torques can be considered equivalent to those in a static situation.

2.3.2 Hip and knee torques

It was important to establish the magnitude and ranges of hip and knee torques reached in NHE testing to be able to design a device capable of accurately and safely assessing strength at these levels. Normative data available for NHE strength testing, collated from over 21,000 tests performed on the NordBord during the 2019-20 European football season, provides a baseline. Median strength values for different football leagues were reported as 425N (interquartile range of 103N), 418N (interquartile range of 86N) and 400N (interquartile range of 101N) for the English Premier League, English Championship League and the UEFA Champions League respectively (VALD performance, 2020). The interquartile ranges reported do not include standard deviations, however, given the assumption of normally distributed data, the interquartile range (Q3-Q1) can be approximated as 1.35 times the standard deviation (Altman & Bland, 1995). Furthermore, assuming the median approximates the mean, adding twice the interquartile range to the median yields a value above the 99th percentile, which is approximately 631N (Altman & Bland, 1995; Wackerly et al., 2008).

Using these normative values, force can be converted into estimated torque using Equation 1. This involves multiplying the distance between the pivot point and the point of force application (in this experimental case the average shank length) by the force. According to De Leva (1996) the typical longitudinal length (from proximal ends) of the shank (knee to ankle) in males is 44.03cm. Therefore, the designed device must be capable of accommodating generated knee torques averaging 187Nm and potentially up to 278Nm (based on the 631N upper threshold), to effectively test elite male athletes.

Moreover, Vald performance has published normative data on the eccentric strength of over 300 professional female athletes, tested in 2021 across elite Australian rules football, rugby league and football teams, where the median eccentric strength force recorded was 276N with an interquartile range of 71N (VALD performance, 2021). Adding twice the interquartile range to the median yields a value above the 99th percentile, which is approximately 418N. According to De Leva (1996) the typical longitudinal length of the shank in females is 43.86cm. Therefore, using **Equation 1** the device must be capable of handling knee torques averaging 121Nm and potentially up to 183Nm (based on the 418N upper threshold), to effectively test elite female professional athletes. This value is likely to represent the upper limit expected during preliminary testing and subsequent data collection within the context of the thesis and the anticipated participant cohort.

$$\mathrm{T}kf - \mathrm{T}ke = \mathrm{F}g \cdot \mathrm{lsin\theta} = \mathrm{F}L \cdot \mathrm{l_{tray}}$$

Equation 1: Torque equation.

T*kf* torque produced by the knee flexors, T*ke* torque produced by the knee extensors, F*g* force applied by gravity, lsinθ horizontal perpendicular distance from knee joint (pivot point) to line of action of gravity, F*L* force applied through the load cells, ltray length of the tray between the pivot point and the load cells.

There is limited research available on hip torque generation during the NHE however a study by Hegyi et al. (2019) used a hamstring testing device (*Hamtech*) in bilateral mode, to report torque levels in different hip angle variations. Specifically, torque levels with the hip flexed at 90° during the NHE were significantly higher compared to when the hip was at 0°, spanning from 0 to 87% of the movement, with a large effect size reported (d_2=2.74 ± 0.85). Moreover, it was observed in Šarabon et al. (2019) that changing the slope of the lower leg support (shank) in the NHE did not alter torque production however an alteration in the hip angle did have an impact on torque values, with a greater hip angle resulting in increased peak torque in both the knee (d=0.46) and the hip (d=0.81).

This suggests that breaking at the hip shifts the position of the centre of mass, leading to an increase in the moment arm of the body's weight around the knee joint, resulting in significantly higher peak knee and hip torques (Šarabon et al., 2019). Additionally, if hip flexion is accelerating, it unloads the knee flexors, reducing the torque they must withstand during the movement, which likely explains why individuals adopt this strategy (Hegyi et al., 2019). Muscle activation patterns can change to compensate for changes in the centre of mass position, thereby altering the torque distribution across the hip and knee joints. Greater activation of the hip extensor muscles, such as the gluteus maximus, gastrocnemius, erector spinae, and adductors can improve an individual's ability to eccentrically control knee movement and maintain knee stability throughout the NHE (Bourne, Williams, et al., 2017; Hegyi et al., 2019), which has implications for obtaining accurate standardised readings. Therefore, the hip flexion angle should be minimised to isolate the hamstrings and ensure accurate torque comparison between cohorts.

2.3.3 Inclination, muscle length and applied torque relationship

In a conventional NHE (**Figure 7**) torque cannot be decoupled from muscle length however the same torque can be reached at different muscle lengths by manipulating the shank angle. The angular mechanism should hypothetically target the hamstrings' capacity to apply torque over the more extended knee angles, where injury is most likely to occur. During a conventional NHE the hamstrings are typically trained at short muscle lengths within 90–110° of knee extension range before the break-point is reached (Ditroilo et al., 2013). Most hamstring injuries occur in the proximal region, which coincides with the point of greatest muscle elongation (Mendiguchia et al., 2015; Woods et al., 2004), suggesting the lengthened hamstring may be more vulnerable to injury. By altering the NHE relative knee angle using an incline slope, the same torques should be reached at a longer muscle length, resulting in a rightward-shift in the length-tension curve independent of overall hamstring strength. In **Figure 8** and **Figure 10** this is shown by the shifting of the simulated torque profile. Conversely, when employing a decline position the same torques will be reached at shorter muscle lengths (**Figure** 9 and **Figure 10**).

Rightward-shifts in the torque-angle relationship could be of critical importance for athletes that require high eccentric hamstring force application at specific knee angles, such as those seen in high-speed running (**Figure 10**) (Baumgart et al., 2021; Kellis & Blazevich, 2022; Marušič et al., 2020). Where the torque is being produced in the muscle is of importance, as lengthening hamstring exercises show the fastest return-to-play and a lower reinjury rate compared with conventional hamstring exercises (Ishøi et al., 2020).

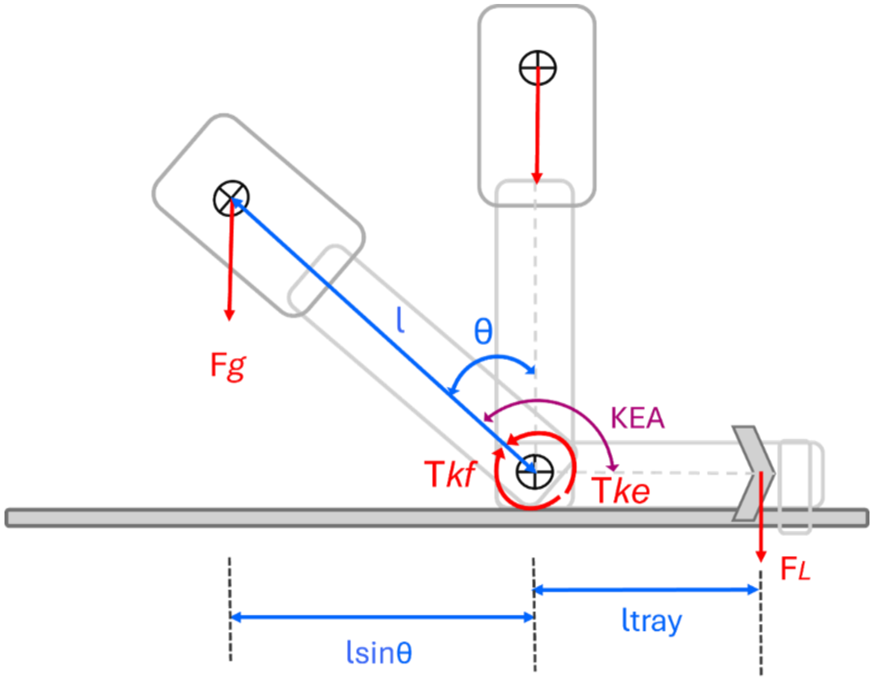


Figure 7

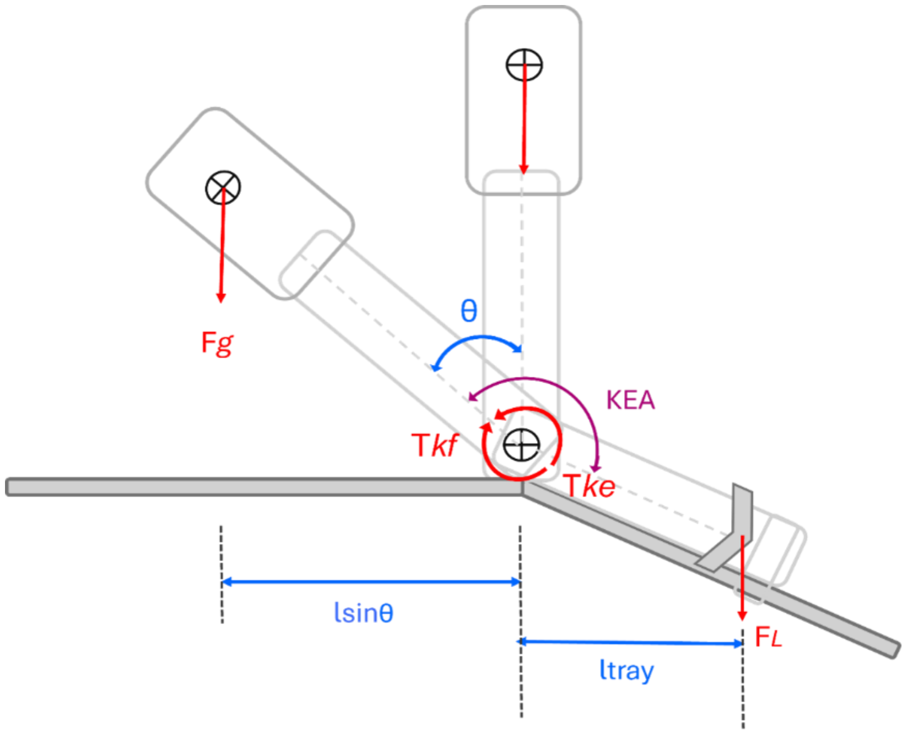
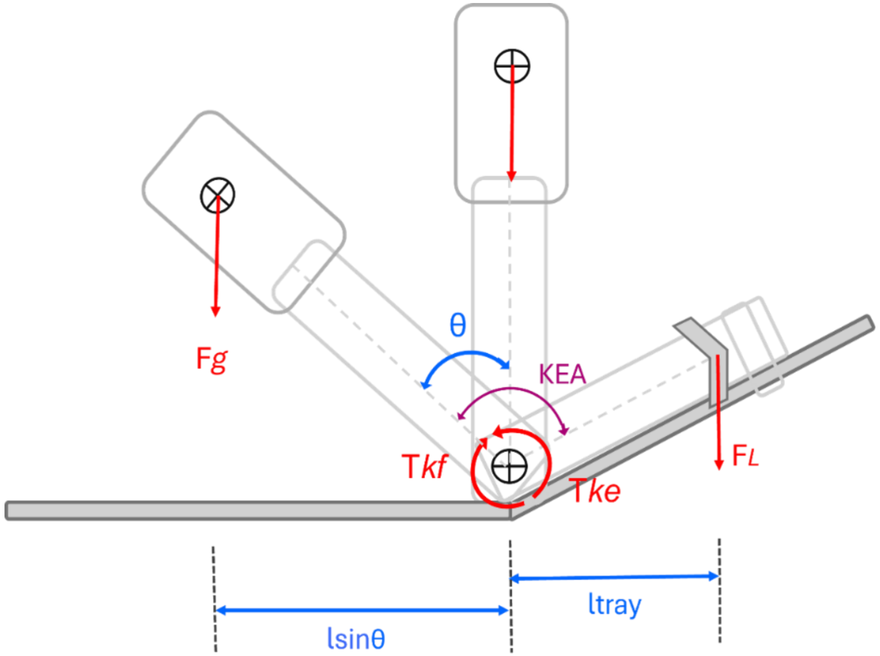


Figure 8

Figure 7: Biomechanical representation of the muscle length-torque relationship during the Nordic hamstring exercise performed on a conventional flat inclination. This serves as a reference model for subsequent incline and decline conditions illustrated in Figures 8-10.

Figure 8: Biomechanical representation of the muscle length-torque relationship during the Nordic hamstring exercise performed on an incline. A rightward-shift in the torque-length relationship is represented, where knee extension angle is greater as knee flexor torque magnitude remains the same.



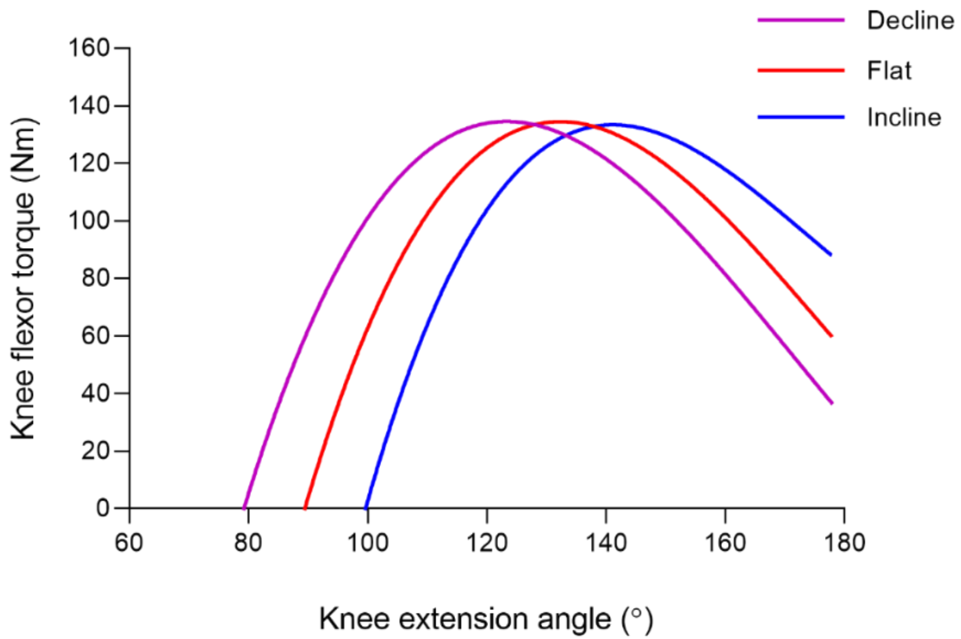


Figure 9

Figure 10

Figure 9: Biomechanical representation of the muscle length-torque relationship during the Nordic hamstring exercise performed on a decline. A leftward-shift in the torque-length relationship is represented: knee extension angle is smaller as knee flexor torque magnitude remains the same.

Figure 10: Schematic representation integrating the hypothesized muscle torque-length relationships from Figures 7-9. Illustrating the expected rightward-shift for the incline slope (blue line), and leftward-shift for the decline slope (purple line) relative to the flat reference (red line)..

F*g* weight of thighs and upper body, l length from the knee joint to the centre of mass, θ thigh angle to vertical, KEA knee extension angle, T*kf* torque produced by the knee flexors, T*ke* torque produced by the knee extensors, F*L* force applied through the load cells, lsinθ horizontal perpendicular distance from knee joint (pivot point) to line of action of gravity, ltray length of the tray between the pivot point and the load cells.

* The small, constant moment generated by the weight of the shank and tray is considered negligible and thus ignored

2.4 Prototype device design principles

Based on the findings and biomechanical NHE framework, the hamstring prototype device was designed using the following foundational key concepts and requirements:

i. **Custom-built dynamometer**: A dynamometer to measure torque about the knee, as torque accounts for both the magnitude of force and the distance from the axis of rotation (lever arm length). This allows for a more standardised measure of joint loading, making results more comparable between individuals of different limb lengths, and ensuring a consistent approach to testing.

ii. **Novel adjustable rig:** A rig with an angular mechanism to adjust the inclination to target the knee flexors capacity to apply torque over extended knee angles, where injury is most likely to occur. Using a graded training intervention protocol across the different inclinations (decline, flat and incline) would support a gradual and progressive rehabilitation process. The inclination angle could be customised based on individual return-to-play criteria and specific injury location, ensuring a tailored and effective recovery strategy.

iii. **Angle measurement**: A precise measure of position to determine the knee and hip angles reached at break-point during the NHE, ensuring accurate testing and exercise monitoring.

2.5 Design framework and specification

The prototype device design framework shown in **Figure 11** was developed considering the limitations of existing devices, biomechanical relationships relevant to hamstring injury and the biomechanics of the NHE. The prototype device design specification shown in **Table 2** defines the detailed requirements of the device's hardware and software requirements, The following sections then explore each of the key features of the framework and specification in more detail.

.

Integration: Integrate inclination, torque and angle into a concurrent measurement system.

Inclination **Adjustable mechanism**		**Adjustable inclinations: decline, flat, incline** ~ *graded training inclinations*
		Precision of angular mechanism adjustments ~ *target the knee flexors effectively at specific angles*
		Robust construction and ergonomic design ~ *durability and ease of use*
		Safety features ~ *prevent accidental slippage or instability*
Torque **Custom-built dynamometer**		**Measure torque about the knee** ~ standardised testing between cohorts
		Load cell calibration ~ *torque measurement accuracy*
		Adjustable weight-bearing frame ~ *accommodate variations in player anatomy and size*
Angle **Knee and hip angle measurements**		**3D analysis measurement system** ~ *capture joint angles throughout the NHE*
		Attachable sensors ~ *thigh and trunk angle data*
		Software ~ *coded programmes for raw data analysis*
		Data visualisation ~ *inform measurement and feedback*

Figure 11: Prototype device design framework

Table 2: Prototype device design specification

Feature	Description	Specification requirement	Purpose/Measurement
Inclination adjustment mechanism	Frame with hole spacing	Non-ferrous materials: plywood (for pilot/Polhemus version) – with a preference for steel (final iteration). 5° spacing over ± 20°range	Modifies the NHE shank angle to perform the NHE on an incline or decline
	Knee cushioning	Provide foam blocks for patella glide cushioning	Provides user comfort
	Rollers	Integrated wheels for portability	Transport of the device between locations
Custom-built dynamometer: Torque	Load Cells	In-line strain gauges (Omega, Engineering Inc. Norwalk, USA) calibrated for 631N/278Nm.	Measures knee flexor force (calculated torque)
	Ankle straps	Straps to hold down ankles	Maintains body position and isolates hamstring contribution
	Pivot point	Rotary mechanism	Promotes consistent joint positioning and allows the trays to rotate
Limb angle measurements	Sensor	2 sensors and holders mounted on the thigh and trunk made to fit	Records trunk-thigh angular raw data
	3D motion capture system	Liberty® Polhemus (Colchester, Vermont, USA): 240Hz Calibration of system to measure orientations of the trunk and thigh relative to an initial vertical kneeling position	Tracks hip and thigh orientation, providing continuous angular kinematic data during the NHE
	Video analysis	High speed camera (Casio-Exlim-F1 camera 60Hz) Motion capture app Kinovea (version 0.815)	Visual confirmation of NHE movement technique
Integration	Acquisition board	Phidget bridge acquisition board (Phidgets Inc, Calgary, Canada): 125Hz sampling rate	Converts analogue load cell signals, and synchronises force and motion data streams
	Data sampling	Software and calibration for integration of data sampled at different frequencies	Enables accurate torque-angle correlation
	Data processing	Custom Excel workflow (Microsoft Corp., Redmond, Washington) and MATLAB script (version R2022b, MathWorks, Inc., Natick, MA)	Outputs calculated variables such as peak torque, torque-angular profile, hip/knee ratios

2.5.1 Angular mechanism for inclination adjustment

The novel rig features a moveable mechanism that allows adjustment of the shank incline to the horizontal at 5° intervals (**Figure 12**). The selected range of plus and minus 20° was determined by considering biomechanical principles and practical usability factors. By offering both decline and inline options, the rig caters for a spectrum of graded intensities and could be applied to both rehabilitation and performance testing and training. While smaller intervals offer finer adjustments and degree measurements, they also complicate the setup process and increase complexity. Conversely, larger intervals limit the specificity of assessing training stimuli changes. Therefore, the 5° intervals allow effective customisation of training protocols without sacrificing usability. From a device stability standpoint, by maintaining appropriate distances between the spacing holes, the rig offers robust support while accommodating the structural demands imposed during the exercise by the user, providing a level of safety, and therefore balancing practicality with effectiveness.

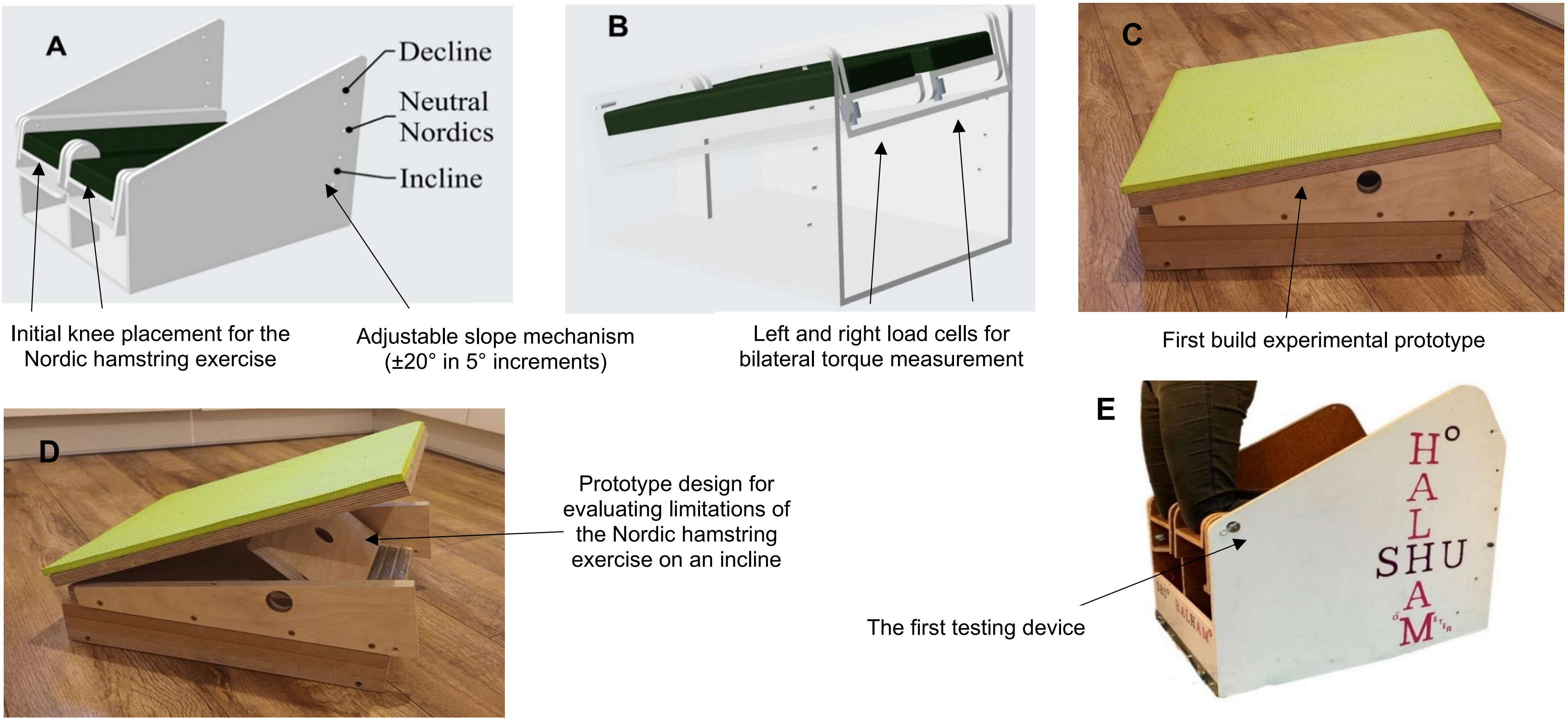


Figure 12: Representation of the HALHAM design process, including development plans and design versions.

Panel (A) shows a computer-aided design of the prototype hamstring device, illustrating the adjustable inclination mechanism used to modify the angle of the platform. Panel (B) represents a cut-away rear view of the same mechanism, demonstrating its adjustable range from minus 20° to plus 20° in 5° increments. Panels (C) and (D) show the construction of the first small-scale prototype, and its experimental set-up, which were used to identify mechanical limitations and evaluate the feasibility of the adjustable inclination system. Panel (E) shows the first main prototype build for participant testing.

2.5.2 Custom built dynamometer

The prototype dynamometer features a flat platform, employing the same method traditionally used during a conventional floor NHE, upon which the ankle angle can be self-determined by the participant i.e. plantar-flexed or dorsi-flexed (**Figure 13**). Notably, research has indicated that ankle position does not significantly influence the normalised muscle activity of the BF_{LH} (124.5% ± 6.2% vs. 128.1 ± 5.0%, p>0.05, d=0.64) or the medial gastrocnemius during the NHE (82.1% ± 3.9% vs. 83.5 ± 4.8%, p>0.05, d=0.32) which means participants can select their preferred ankle position without muscle architecture being influenced (Comfort et al., 2017). During use of the device, alignment is achieved by positioning the lateral epicondyle of the knee with the pivot point before commencement of the exercise. The ankle straps were positioned 0.6m from the pivot point at the front of the rig position, ensuring optimal biomechanical alignment and participant comfort (**Figure 13**).

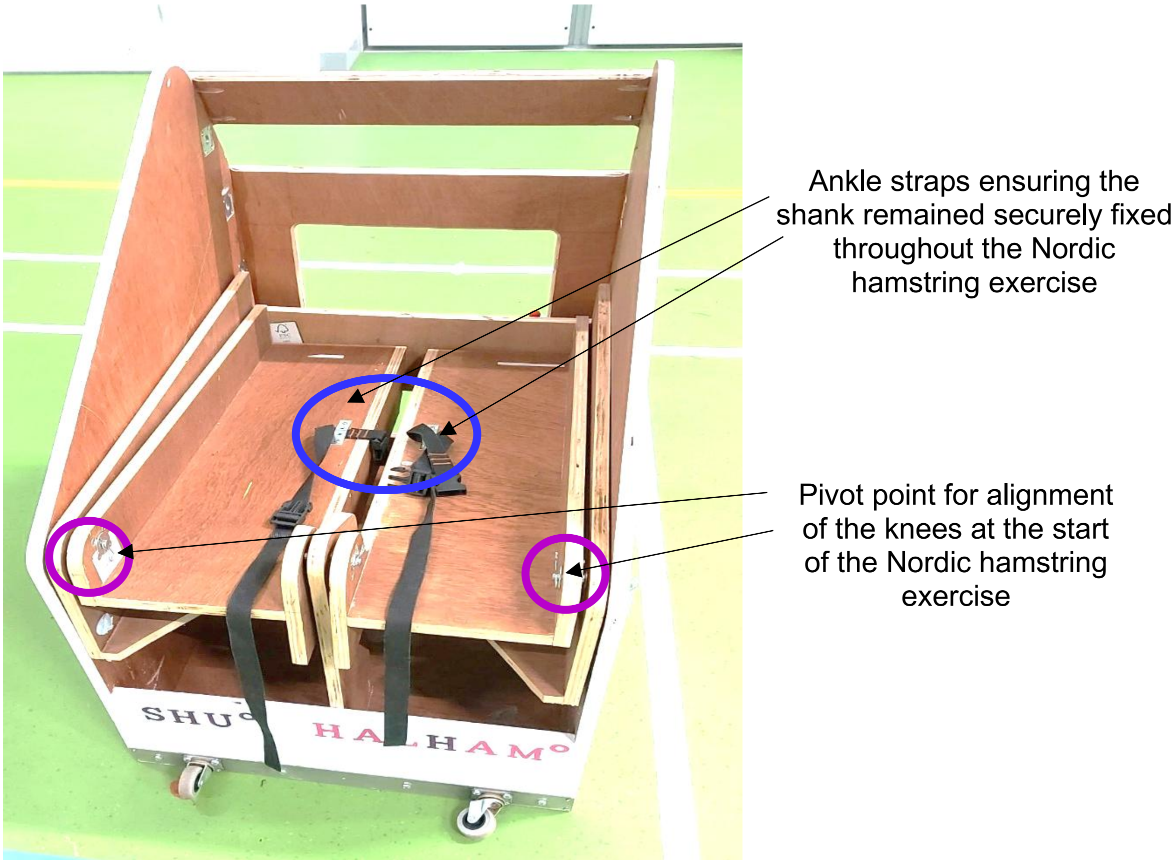


Figure 13: Ankle strap position and the knee pivot point alignment.

2.5.3 Torque calibration and measurement

To enable direct measurement of the torque generated at the knee, independent of leg length, a rotary mechanism was implemented. The torque was converted to a linear force through the pivot system detailed in **Figure 14**.

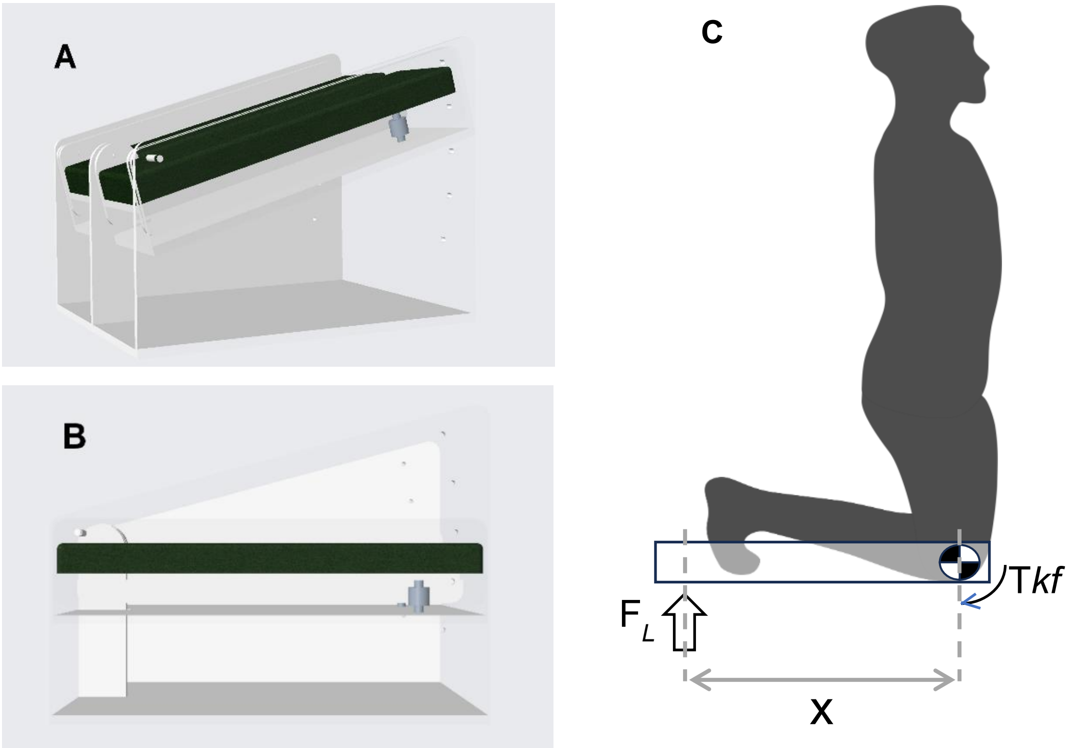


Figure 14: A computer-aided design of the prototype hamstring device which shows the moveable tray that is free to rotate through a pivot system (A and B), and the location of the load cells (B), with a biomechanical representation of the pivot system (C).

F_L force applied through the load cells, x perpendicular distance between the pivot (knee joint) and the load cells, T*kf* torque produced by the knee flexors.

The load cells measured eccentric torque from both limbs and detected bilateral asymmetries. To ensure an accurate force output from the load cells, a calibration process was performed. Calibrated weight plates ranging from 0kg to 40.15kg (reflecting the anticipated loads expected to be applied to the system) were incrementally suspended from a rigid mounting point on a support frame. This setup ensured that each applied load was vertically aligned and reproducible. For each known mass, the corresponding voltage output was recorded using the load cell acquisition software. This generated a range equivalent to approximately 393.79N range of force per load cell (**Figure 15**) and was comparable to the expected testing values discussed earlier in the chapter of a bilateral load of 631N/278Nm (315N, 139Nm per load cell)

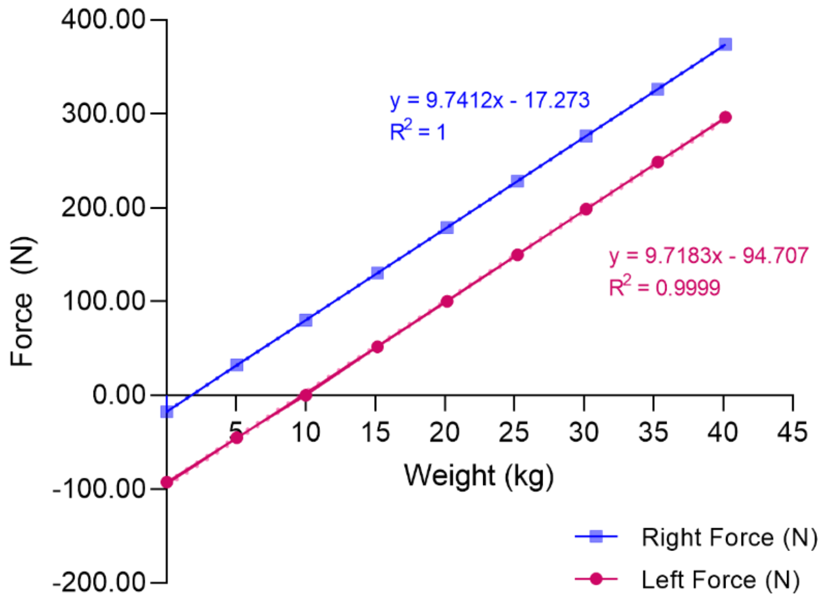


Figure 15: Calibration of left and right strain-gauge load cells showing the linear relationship between known applied loads and corresponding voltage output, with lines of best fit. This plot verifies the accuracy and linearity of the load cells used to measure eccentric knee torque, providing the calibration factors required to convert voltage to force and subsequently torque. Establishing this relationship ensured reliable and valid measurement of bilateral torque during testing.

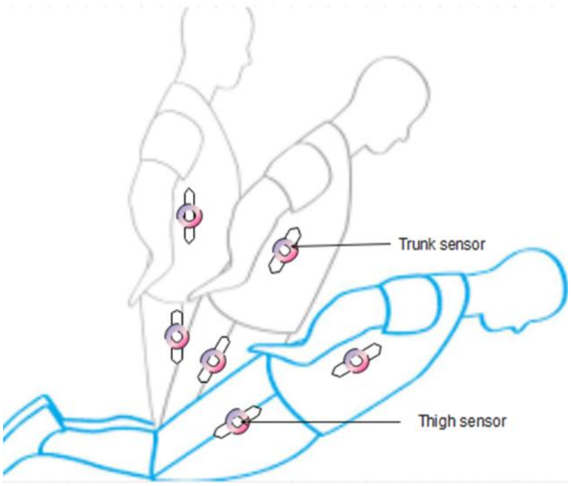
Figure 15 presents the calibration factors for each load cell in compression and tension. Subsequently, a MATLAB script (version R2022b, MathWorks, Inc., Natick, MA) processed the raw force data acquired from the right and left load cells and applied the scale calibration factor (right scale=9.7412, left scale=9.7183) to obtain calibrated force values and plot the force traces. Since the measurement point serves as the zero reference, the offset was deemed unimportant. Given the known distance between the pivot point and the in-line strain gauge load cells (0.661m), the measured force was converted to torque. The resulting plots then displayed the calibrated torque traces starting at 0 on the y-axis. Furthermore, the data were normalised to each individual player’s body mass (BM) to account for variations and standardise comparisons of performance outcomes.

2.5.4 Limb angle measurement

A reference system was required to track the movement of the thigh and trunk during the NHE to measure angular displacement. Although the NHE primarily occurs in the sagittal plane, a 3D kinematic system was chosen to ensure accurate measurement of angular displacement and alignment, since even small out-of-plane motions (e.g. hip rotation or trunk deviation) can affect the accuracy of derived 2D angles (Cescon et al., 2015). The system needed to be capable of capturing the NHE movement in a 3-dimensional space with high temporal resolution, providing reliable kinematic data for analysis. The Liberty® 3-dimensional motion tracking system developed by Polhemus (Colchester, Vermont, USA) was chosen due to its laboratory-grade quality. Its electromagnetic field maps limb position of the thigh and trunk using two attached wired sensors. The Polhemus Liberty® software was used to collect kinematic data from the two sensors sampled at 240Hz and measured the sensors' orientation relative to its source frame (static accuracy of 0.15°), with the hemisphere of operation set to the right hemisphere relative to the source box. The system was calibrated to measure the orientations of the trunk and thigh relative to the source frames.

As magnetic-based systems can be disturbed by metallic objects (Nixon et al., 1998) any capture areas were scanned first using the sensors to check the absence of distortion, and the prototype was purposefully made primarily of non-ferrous material (wood). A boresight command was used to reset the rotation matrix for the correct station at the start of each NHE trial. The rotation matrix represents the orientation of the sensors relative to the exercise (the reference frame). By resetting the rotation matrix at the start of each trial, the sensors can be realigned to the correct reference position, and any potential drift or misalignment in the Polhemus sensor system can be corrected, ensuring the accuracy and reliability of the data collected.

NHE kinematic data collection necessitates the use of both thigh and trunk sensors. The thigh sensor identifies the BPA and angular velocity during the exercise (descent speed) while the trunk sensor acts to identify any flexion at the hip, which are key metrics for assessing NHE biomechanics. Although 3D motion capture was used, analysis was constrained to the sagittal plane, as this represents the principal direction of motion and load during the NHE. Nonetheless, the 3D setup enhanced fidelity and alignment accuracy, ensuring that even planar data reflected true motion rather than projection artefacts (Cescon et al., 2015; Wheare et al., 2021). Consistent and accurate sensor positioning was critical for capturing precise changes in joint angles, particularly at the point where the knee transitioned from flexion to extension, and subsequently the accurate identification of the break point. This was important, as previous research has shown that a 5-6° change in the angle at break point following a training intervention is considered clinically meaningful (Delahunt et al., 2016).



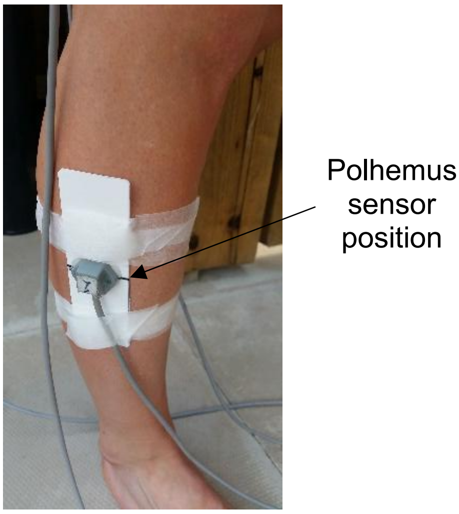


Figure 16: Illustration of thigh and trunk sensor positioning.

Each sensor was glued in place on to the middle of a pliable plastic custom-made sensor plate (**Figure 16**). To ensure consistency the thigh and trunk sensors were placed in symmetrical positions relative to chosen anatomical landmarks. The thigh sensor was positioned laterally on the upper leg at equal distance away from the greater trochanter and lateral epicondyle (**Figure 16**). The trunk sensor was then positioned laterally at an equal distance from the greater trochanter to the shoulder bursa before the commencement of any trials (**Figure 16**). Alignment of the sensors was achieved by palpating and marking the chosen reference landmarks, specifically the bony prominences of the lateral epicondyle, greater trochanter and shoulder bursa, with midpoints determined to the nearest millimetre using a flexible, medical-grade measuring tape. These midpoints were then marked with a dermatological skin marker before affixing the sensor plates with hypoallergenic medical tape, ensuring stable and consistent placement. Using these anatomical locations and equal measured distances from each landmark ensured participants began the NHE from a neutral position across all trials (Weygers et al., 2020). This type of consistency helped ensure uniformity in any data collection and accuracy within statistical analysis.

2.6 Chapter conclusion statement

This chapter has outlined the design specification of a custom-built hamstring pilot device tailored for NHE testing and training. By identifying the gaps in the current literature on hamstring injuries, the device was designed to overcome the shortcomings observed in existing current hamstring devices.

Figure 17: First iteration of the prototype device developed for Nordic hamstring exercise assessment.

The first iteration of the prototype seen in **Figure 17** was designed to manipulate the torque-angle relationship through an inclination mechanism, aimed at eliciting torque production at longer muscle lengths, addressing the key relationship between torque and muscle length, overlooked in conventional devices. The prototype device, *named* ‘HA*L*HAM°’ was used to explore the NHE and its relationship to HSI injury risk factors. To ensure academic rigour any device limitations or challenges were documented throughout the testing process. This approach allowed for necessary modifications to be made, improving functionality while ensuring validity.

Chapter 3

Study 1 - Establishing Key Metrics and Terminology for Nordic Hamstring Exercise Assessment using a Prototype Hamstring Device.

Elements of this chapter have been published in the article titled, "Agreement between methods and terminology used to assess the kinematics of the Nordic hamstring exercise" in *Journal of Sports Sciences* (https://doi.org/10.1080/02640414.2021.1968127).

Despite extensive research examining the NHE, there remains little agreement on which metrics best characterise NHE performance and technique. Differences in device selection, metric definitions and analytical methods have created inconsistencies across studies, limiting the ability to compare findings and establish standardised benchmarks. Consequently, there was a need to systematically evaluate multiple kinematic and kinetic variables collected concurrently to determine their utility in assessing NHE performance and to identify valid markers of eccentric neuromuscular control.

3.1 Chapter aim

The aim of this chapter was to establish standardised methods, terminology and metrics for assessing eccentric hamstring performance and exercise technique during the NHE.

3.1.1 Study objectives

i. Utilise the HA*L*HAM° prototype hamstring device to assess a range of kinetic and kinematic metrics during the NHE.

ii. Identify valid metrics that best reflect eccentric hamstring performance and technique control during the NHE.

3.1.2 Hypothesis

i. Specific angular-torque metrics (e.g. break -torque angle) will provide valid and low-variability indicators of eccentric hamstring performance, rather than relying solely on traditional metrics (e.g. peak torque alone)

ii. Technique control and variability can be quantified by measuring hip flexion and descent velocity during the NHE.

3.2 Introduction

Recent research on the NHE has predominantly centred on using kinetic and/or kinematic variables to assess movement dynamics and training effects (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Jeffery, 2018; Lee et al., 2017, 2018; McGrath et al., 2020; Muggleton, 2015; Šarabon et al., 2019; Sconce et al., 2015). However, comparisons between similar NHE studies are challenging due to inconsistent device use and method choice, coupled with ambiguity and variability in terminology across the literature. Kinematic measures often differ in definition and application, with metrics sometimes used interchangeably across studies. This lack of agreement creates difficulties when attempting to draw meaningful comparisons among findings and prevents the establishment of standardised benchmarks (**Table 3**).

It is well documented in the research that eccentric strength is an important concept of NHE performance (Alonso-Fernandez et al., 2018; Askling et al., 2003; Bourne et al., 2015; Carmichael et al., 2022; Cuthbert et al., 2020b; Khairunnisa et al., 2023; Opar et al., 2015; Vianna et al., 2021), with a 'loss of control' indicating that torque has exceeded the capability of the knee flexor muscles, causing the participant to 'break' and fall to the floor. As discussed in **Chapter 1**, Sconce et al., (2015) validated the BPA as a field-based proxy measure for eccentric knee flexor torque, demonstrating a strong association with isokinetic dynamometry. A lower BPA (greater knee extension relative to the forward horizontal) strongly correlated to a larger eccentric knee flexor torque (average of right and left limbs) (r^2=0.65, n=16, p<0.001). Visual assessment of BPA is useful for those practitioners with limited equipment, providing an approximate indication of an athlete's eccentric hamstring strength. Smartphone applications such as iOS Nordics software (Balsalobre, 2017) which digitise NHE video clips into a two-dimensional space, provide a low-cost alternative to laboratory devices. While this application provides an indirect measure of moment, no research has explored how well such proxy values correspond to knee flexor torque values from an instrumented hamstring device, making comparison to HSI risk factor force values given in the literature challenging. There are other limitations to this approach such as the validity of measures for those athletes that can reach full knee extension during a bodyweight NHE. Additionally, the inter-participant variation in NHE technique, where hip position control and movement speed can influence muscle length and torque production (Hegyi et al., 2019; Marušič et al., 2020; Šarabon et al., 2019) poses a problem for determining an accurate BPA.

In order to examine NHE performance, metrics relating to angle and velocity have most commonly been applied to measure NHE loss of control; these include BPA and angles at specific velocities (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Lee et al., 2017, 2018; McGrath et al., 2020; Sconce et al., 2015). Lee et al., (2017, 2018) employed 2D motion analysis in the CUHK test to quantify the BPA during the NHE. Initially, a high-speed camera (Casio EX-F1, Japan) was used, with video clips digitised using the Ariel motion analysis computer software (Ariel Dynamics, Inc., CA, USA). In a later iteration of the test, a smartphone camera (iPhone 5s) was used to capture sagittal plane movement (Lee et al., 2018) increasing the practicability of the method. Reflective markers were placed on key anatomical landmarks (hip, knee and ankle) and knee angle was defined as the angle between the hip and knee markers relative to the participants initial upright (vertical) position. The break-point was identified as the moment angular velocity around the knee exceeded $10 deg \cdot s^{-1}$, signifying the onset of rapid descent and neuromuscular failure. This threshold was derived from pilot testing and estimation of when participants could no longer eccentrically resist the forward fall (Lee et al., 2017, 2018).

Unlike the visual inspection method used by Sconce et al., (2015), which identified BPA based on a perceived loss of control relative to the horizontal, the CUHK approach employed a defined angular velocity threshold, offering a more objective and reproducible metric. The smartphone CUHK test has demonstrated high test-retest reliability (ICC=0.94), strong concurrent validity with isokinetic eccentric hamstring peak torque at 30deg·s^{-1} (r=0.88, p<0.001), and sensitivity to fatigue induced performance changes (Lee et al., 2018). No consensus exists regarding the optimal reference angle system, whether to define BPA from vertical, horizontal or use full range 0-180° joint angles. Such methodological variability complicates comparisons between studies. However, when examining torque-length relationships, using 0-180° angles may be preferable, as it accounts for changes in shank angles and better captures potential shifts in BPA.

In other research, motion capture and custom electrogoniometry systems have been employed to measure kinematics (Alt et al., 2018; Delahunt et al., 2016; McGrath et al., 2020; Šarabon et al., 2019). Notably, Ditroilo et al. (2013) was the first study to use a single axis electrogoniometer and data acquisition system to record NHE knee joint angle. The metric most closely relating to BPA was the angle characterising the end of trunk control termed, 'angle at downward acceleration' (angle at DWA) identified as the point on the curve of a graph where a sudden increase in velocity occurred. This point was determined by computing a slope function over adjacent 200ms time windows (100ms overlap). The slope difference between one-time window and the previous one was calculated. The angle corresponding to the initial point of the time window that yielded the highest slope difference was reported as the angle at DWA (**Table 3**).

3.1 Selection of kinematic metrics for review

Kinematics metrics used to assess NHE performance were identified through a focused review of the literature (**Table 3**). Given the limited number of studies reporting kinematic outcomes during the NHE, all peer-reviewed research presenting quantitative kinematic data was considered for inclusion. Metrics were selected based on their relevance to the assessment of eccentric hamstring function, typically using joint angle or angle velocity measures to assess the Nordic hamstring exercise. All included studies followed standard NHE procedures and reported sufficient methodological detail. For each study the following information was extracted and tabulated: the definition of each kinematic metric, the equipment and calculation method used, participant characteristics and reported outcomes (mean ± standard deviation or interquartile ranges where available). This approach ensured that the review captured all relevant kinematic variables for the NHE and provided a basis for standardising terminology, definitions and measurement methods in subsequent experimental chapters. The review was systematic but not formal and was guided by the principle of capturing all reported kinematic metrics relating to the NHE to inform device development, metric selection, and standardisation.

Table 3: Kinematic metrics and their definitions used in Nordic hamstring exercise literature. Average results are reported as Mean or Mean and standard deviation for each metric.

Terminology	Definition	Equipment and Calculation Method	Average results (Mean ± SD)
BPA (Sconce et al., 2015)	The knee angle relative to the forward horizontal at which the individual can no longer resist the increasing gravitational moment and falls to the floor	- Partner assisted NHE - 2D motion capture (video-based) and Quintic software used for joint-angle analysis - Knee angle calculated relative to the horizontal plane; visually determined - NHE starting position defined as 90° at upright with full horizontal extension being 0°: *Smaller angles indicated that the participant was closer to the floor at break-point*	n=16 male (n=7) and female (n=9) soccer players BPA=41 ± 8.1°
CUHK Nordic break-point test (Lee et al., 2017) (Lee et al., 2018)	The angle between the line joining hip and knee markers and initial vertical position of each participant. Angle metric determined by the first appearance of the angular velocity that is greater than $10 deg.s^{-1}$	- Partner/platform assisted NHE - 2D motion capture (video-based)/smartphone video and - Ariel software used for angular-velocity analysis - Knee angle calculated relative to the vertical plane; determined by the point where angular velocity exceeds $10 deg.s^{-1}$ - NHE starting position defined as 0° upright with full horizontal extension being 90°: *Larger angles indicated that the participant was closer to the floor at break-point*	n=33 male 2nd division football league players CUHK test=17.76 ± 6.61° (Lee et al., 2017) n=25 male professional football players CUHK test=40.78 ± 15.77° (Lee et al., 2018)

Angle at DWA (Ditroilo et al., 2013) (Delahunt et al., 2016)	The angle characterising the point in time when the control of the forward fall is lost, translating into a sudden increase in downward velocity	- Partner assisted NHE - A single-axis electrogoniometer recorded the knee joint angle and sEMG monitored angular displacement (Ditroilo et al., 2013) - Custom Codamotion software used for knee angular displacement and velocity analysis (Delahunt et al., 2016) - Angle at DWA calculated by the angle corresponding to the initial point of the time window that yielded the highest slope difference - NHE starting position defined as 90° at upright with full horizontal extension being 0°	n=18 male university students Angle at DWA=68.1 ± 8.0° (Ditroilo et al., 2013) n=29 healthy recreationally active males Angle at DWA=76.9 ± 3.8° (Delahunt et al., 2016)
pVelocity (Ditroilo et al., 2013) (Delahunt et al., 2016)	The maximum knee joint velocity	- Partner assisted NHE - A single-axis electrogoniometer recorded the knee joint angle and sEMG monitored angular displacement (Ditroilo et al., 2013) - Custom Codamotion software used for knee angular displacement and velocity analysis (Delahunt et al., 2016)	n=18 male university students pVelocity=81.3 ± 23.8deg.s^{-1} (Ditroilo et al., 2013) n=29 healthy recreationally active males

		- The maximum knee joint velocity was identified as the peak value on the velocity-time curve - NHE starting position defined as 90° at upright with full horizontal extension being 0°	pVelocity=117.7 ± 16.4deg.s^{-1} (Delahunt et al., 2016)
angle@pVelocity (Delahunt et al., 2016) (McGrath et al., 2020)	The knee joint angle at which peak velocity occurs	- Partner assisted NHE - Custom Codamotion software used for knee angular displacement and velocity analysis - The knee joint angle corresponding to the point of peak velocity on the velocity-time curve was identified (Delahunt et al., 2016) - Hamstring device (NordBord) NHE - Single-leg NHE performed - Vicon 3D motion capture and lower body plug-in gait model used for angular-velocity of the knee joint analysis - Peak knee joint velocity was extracted from the time-series data, with the corresponding joint angle identified - NHE starting position defined as 90° at upright with full horizontal extension being 0° (McGrath et al., 2020)	n=29 healthy recreationally active males angle@pVelocity = 41.8 ± 5.6° (Delahunt et al., 2016) n=33 elite male rugby league players angle@pVelocity = 37.7° (IQR 42-32°) (McGrath et al., 2020)

Knee angle (°) at 20deg.s^{-1} (McGrath et al., 2020)	The angle corresponding to the start of the NHE forward movement in a maximal effort	- Hamstring device (NordBord) NHE - Single-leg NHE performed - Vicon 3D motion capture and lower body plug-in gait used for angular-velocity analysis - The corresponding knee joint angle was extracted from the time-series data at the instant the thigh reached an angular velocity of 20deg.s^{-1} - NHE starting position defined as 90° at upright with full horizontal extension being 0°	n=33 elite male rugby league players Mean knee angle at 20deg.s^{-1} =80.43° (IQR 85-76°)
Knee angle (°) at 60deg.s^{-1} (McGrath et al., 2020)	The angle corresponding to the period when the athlete begins to accelerate during the NHE movement	- Hamstring device (NordBord) NHE - Single-leg NHE performed - Vicon 3D motion capture and lower body plug-in gait used for angular-velocity analysis - The corresponding knee joint angle was extracted from the time-series data at the instant the thigh reached an angular velocity of 60deg.s^{-1} - NHE starting position defined as 90° at upright with full horizontal extension being 0°	n=33 elite male rugby league players Knee angle at 60deg.s^{-1} =67.26° (IQR 72-61°)
Elapsed time period (ms)	The time under load during the contraction between the	- Hamstring device (NordBord) NHE - Single-leg NHE performed	n=33 elite male rugby league players

between 20 - 60deg.s^{-1} (McGrath et al., 2020)	start of the NHE movement and when the athlete begins to accelerate	- Vicon 3D motion capture and lower body plug-in gait used for angular-velocity analysis - The elapsed time period (milliseconds) for the knee joint angular velocity to increase from 20–60 deg.s^{-1} in the time-series data was calculated - NHE starting position defined as 90° at upright with full horizontal extension being 0°	Elapsed time period between 20-60deg.s^{-1} = 369.1ms (IQR 288-430ms)
Elapsed time period (ms) between 20deg.s^{-1} - peak velocity (McGrath et al., 2020)	The time under load during the contraction between the start of the NHE forward movement and peak velocity	- Hamstring device (NordBord) NHE - Single-leg NHE performed - Vicon 3D motion capture and lower body plug-in gait used for angular-velocity analysis - The elapsed time period for the knee joint angular velocity to increase from 20◦/s to peak velocity in the time-series data was calculated - NHE starting position defined as 90° at upright with full horizontal extension being 0°	n=33 elite male rugby league players Elapsed time period between 20°/s-peak velocity = 623.3ms (IQR 555-723ms)
t_{NHE} (s) during NHE (Alt et al., 2018)	The time under tension achieved during each NHE repetition	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis	n=16 regional to national class male sprinters Assisted NHE (6 sessions) = 6.8 ± 0.6s

		- 3D motion capture (Vicon Peak motus) used for angular-velocity analysis - Time under tension was determined from the moment-time curve data and was calculated as the duration of each NHE rep, determined between the start and end points identified from the first derivatives of the moment-time and knee flexion angle-time curves - NHE starting position defined as 0° upright with full horizontal extension being 90°:	Unassisted NHE (6 sessions) =4.4 ± 1.1s
ROM_{knee} (°) (Alt et al., 2018)	The ROM of the knee joint during each NHE repetition. The	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis - 3D motion capture (Vicon Peak motus) used for angular-velocity analysis - Range of knee motion was calculated from the knee-flexion angle-time curve between the start point (identified from the first derivatives of the moment-time and knee flexion angle-time curves to the knee flexion angle at DWA	n=16 regional to national class male sprinters Assisted NHE (*1 session) = 81.44 ± 5.5° Unassisted NHE (6 sessions) =72.7 ± 8.3°

		- The knee flexion angle at DWA was identified as the highest angular acceleration in the knee extension velocity-knee flexion angle-time curve	
Mean ω_{KE} (deg.s^{-1}) (Alt et al., 2018)	The mean knee extension velocity	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis - 3D motion capture (Vicon Peak motus) used for angular-velocity analysis - Mean ω_{KE} was calculated as the arithmetic mean of all instantaneous knee extension angular velocity values from knee flexion angle-time curves across the full eccentric phase of the NHE	n=16 regional to national class male sprinters Assisted NHE (*1 session) = 12.2 ± 1.1°/s Unassisted NHE (6 sessions) =17.3 ± 4.9°/s
ROM $_{hip}$ (°) (Alt et al., 2018)	The ROM of the hip joint achieved during each NHE repetition	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis - 3D motion capture (Vicon Peak motus) used for angular-velocity analysis	n=16 regional to national class male sprinters Assisted NHE (*1 session) = 10.8 ±4.5° Unassisted NHE (6 sessions) =15.9 ± 6.3°

		- The ROM of the hip joint was calculated as the total change in hip flexion angle, derived from the hip angle-time curve, across the full eccentric phase of the NHE	
HF_{max} (°) (Alt et al., 2018)	The maximum hip flexion angle	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis - 3D motion capture (Vicon Peak motus) used for angular-velocity analysis - Calculated as the maximum hip flexion angle reached at any point in the hip-angle term curve across the full eccentric phase of the NHE	n=16 regional to national class male sprinters Assisted NHE (*1 session) = 9.2 ± 6.8° Unassisted NHE (6 sessions) =17.0 ± 8.2°
ROM_{DWA} (%) (Alt et al., 2018)	% of ROM to DWA in relation to the ROM achieved by the knee joint	- Rope-assisted and unassisted NHE performed on a dynamometer (IsoMed2000) and lounger - Dynamometer captured raw angle and moment data, processed using custom C++ software for analysis - 3D motion capture (Vicon Peak motus) used for angular-velocity analysis - Calculated from the knee-flexion angle-time curve as the range of motion from the start point (identified from	n=16 regional to national class male sprinters Assisted NHE (*1 session) = 99.6 ± 1.8% Unassisted NHE (6 sessions) =68.5 ± 24.4%

		the first derivatives of the moment-time and knee flexion angle-time curves) to the knee flexion angle at DWA, expressed as a percentage of the total knee ROM in that repetition.	

SD standard deviation, BPA break-point angle, n number, ° degrees, CUHK Chinese University of Hong Kong, deg.s^{-1} degrees per second, DWA downward acceleration, pVelocity peak knee angular velocity, NHE Nordic hamstring exercise, IQR interquartile range, ms milliseconds, t_{NHE} time under tension during Nordic hamstring exercise, s seconds, ROM_{knee} range of motion of the knee joint, Mean ω_{KE} mean knee extension velocity , ROM_{hip} range of motion of the hip joint, HF_{max} maximum hip flexion, ROM_{DWA} range of motion to downward acceleration in relation to range of motion of the knee joint, % percentage.

There is limited research on simultaneous, concurrent measurement of both kinetic and kinematic variables whilst performing the NHE. Whilst investigating the determinants of hamstring fascicle length, McGrath et al. (2020) utilised a hamstring device with load cells to measure eccentric knee flexor strength during a NHE (NordBord) to record average peak force across three repetitions. 3D motion capture documented kinematics, specifically the corresponding knee angle at 20deg.s^{-1} (classed as the start of the movement), 60deg.s^{-1} (the period where the athlete begins to 'accelerate') and peak angular velocity (classed as the '*loss of control'* of the movement). BPA was referred to as the 'angle of loss of control', which would indicate that the peak angular velocity metric was used, according to the previous definitions in the study. However, the loss of control metric used to define break point in previous research, such as in Sconce et al., (2015) was determined visually from video footage using motion analysis software, rather than from 3D motion capture. In Sconce et al., (2015) sagittal plane video footage was analysed in Quintic Biomechanics v17 (Coventry, UK), with the BPA identified by eye from the point where the participant could no longer resist the forward fall. In contrast, Lee et al., (2018) calculated the BPA objectively from kinematic data, using the Ariel Performance Analysis System (Ariel Dynamics, Inc., CA, USA), defining it as the first instance where knee extension velocity exceeded 10deg·s^{-1}. This definition is unrelatable to the velocity measures used in McGrath et al. (2020), where a threshold velocity of 20deg.s^{-1} was only regarded as the start of the NHE movement, not the break point.

Due to their practical value in the field and lower cost, there has been a rise in the utility of portable devices to assess eccentric strength during the NHE, replacing the traditional use of isokinetic dynamometry to determine knee flexor torque. However, peak torque can only be reached within the range of motion of the NHE action (Cuthbert et al., 2020a) before the participant 'breaks' and falls, compared to the range of motion available through the action performed on dynamometry. Therefore, *break-torque* angle (BTA) during a NHE action could be a more useful determinant of where muscle failure is occurring rather than angle of peak torque on dynamometry. Where the torque is being produced in the muscle is of importance as current research suggests having strong and long hamstring muscles is effectual for injury prevention and a faster return-to-play following injury (Maeo et al., 2021; Marušič et al., 2020; Raiteri et al., 2021; Tyler et al., 2017). This study aims to compare the utility of different metrics to explain NHE performance and technique by comparing several kinetic and kinematic variables collected concurrently. Subsequently, this study aims to propose a standardised, consolidated list of kinematic variables for assessing the NHE, enabling easier comparison between studies. Correlation analyses will identify which variables are strongly associated and which provide distinct information, allowing the removal of redundant measures and the selection of the most informative metrics for consistent reporting (**Table 4**).

3.2 Methods

The NHE was performed on the custom-made HA*L*HAM° equipped with in-line strain gauge load cells (Omega, Engineering Inc. Norwalk, USA) attached at the rear in a fixed position relative to the knee to measure torque. The transducers were factory-calibrated and therefore will provide the same force measurements as other existing validated hamstring devices (Opar et al., 2013; Lodge et al., 2020). A laboratory grade 3-dimensional motion tracking system (Liberty® Polhemus, Colchester, Vermont, USA) was integrated with the NHE device and used as the reference measurement system for the kinematic variables. As magnetic-based systems can be disturbed by metallic objects (Nixon et al., 1998) the capture areas were scanned first using the sensors to confirm the absence of distortion. For this reason, the NHE device was manufactured primarily of non-ferrous materials. Polhemus Liberty® software was used to collect orientation data at 240Hz from two sensors located at the thigh (positioned laterally on the upper leg equidistant from the greater trochanter and lateral femoral epicondyle) and the trunk (positioned laterally equidistant from the greater trochanter and the shoulder bursa).

Calibration involved positioning both sensors in a predefined anatomically neutral position (vertical kneeling posture) and zeroing the orientation outputs to establish baseline references for subsequent measurements of the trunk and thigh. Raw data were sampled at 125Hz via a Phidget Bridge data acquisition board (Phidgets Inc., Calgary, Canada) then exported in .CSV format, and processed in Excel spreadsheets (Microsoft Corp., Redmond, Washington) on a personal computer. As the integration of data was sampled at different frequencies, calibration also included synchronising the load cell and motion capture data (force and angle) via a common event marker (a sensor tap prior to NHE commencement). to ensure accurate temporal alignment and meaningful interpretation of the combined data set. For comparison, and to visually verify any data discrepancies, the BPA was determined using a high-speed camera (Casio Exlim-F1 camera 60Hz) and video analysis software (Kinovea Version 0.8.15) to determine the angle at which visual loss of control occurred from the greater trochanter (hip) to the lateral femoral condyle (knee) relative to the horizontal.

Table 4: Proposed agreement of terminology and definitions to assess the kinetics and kinematics of the Nordic hamstring exercise action.

Terminology	Definition	Equation
Kinetics		
Peak force (N)	NHE bilateral maximum force value	$F_{peak} = \max(F_{left} + F_{right})$
Peak torque (Nm)	NHE bilateral maximum torque value	$T_{peak} = F_{peak} \times r$
Peak torque/kg (Nm/kg)	NHE bilateral maximum torque value normalised to body mass	$T_{norm} = \frac{T_{peak}}{\text{body mass}}$
Kinematics		
BPA (°)	The knee angle at which the individual can no longer resist the increasing gravitational moment and falls to the floor	Measured from the knee joint relative to the horizontal (full extension=180°)
BTA (°)	A new term to represent the definitive peak torque value and its corresponding thigh angle. A valid measure must show a clear torque peak point and subsequent drop-off representing a clear loss of NHE control	Thigh angle at T_{peak} with torque drop-off
RTA (°)	The angle between the thigh and the trunk throughout the NHE ROM, representing hip angle	$\text{RTA} = \lvert\theta_{thigh} - \theta_{trunk}\rvert$
AVK ($\text{deg}\cdot\text{s}^{-1}$)	Represents the angular velocity of the knee joint throughout the NHE	$\text{AVK} = \frac{d\theta_{knee}}{dt}$
fAcc ($\text{deg}\cdot\text{s}^{-2}$)	The point at which angular acceleration first starts to increase on the curve of a graph, manually picking out the time point that shows the first instance	First increase in $\left(\frac{d^2\theta_{knee}}{dt^2}\right)$

	of significant acceleration. Representing the first loss of control occurring in the NHE action	
angle@fAcc (°)	The angle at which fAcc occurs	Knee angle at fAcc
eAcc (deg·s^{-2})	The elbow point manually picked out on the acceleration curve representing the greatest release of NHE control occurring	Point of greatest change in $\frac{d^2\theta_{knee}}{dt^2}$
angle@eAcc (°)	The angle at which eAcc occurs	Knee angle at eAcc
pAcc (deg·s^{-2})	The maximum acceleration value	max $\left(\frac{d^2\theta_{knee}}{dt^2}\right)$
angle@pAcc (°)	The angle at which pAcc occurs	Knee angle at pAcc
PVelocity (deg·s^{-1})	The maximum knee joint angular velocity	max $\left(\frac{d\theta_{knee}}{dt}\right)$
angle@pVelocity (°)	The knee joint angle at which peak velocity occurs	Knee angle at pVelocity
angle@last10deg·s^{-1} (°)	Last instance of 10deg·s^{-1} before a constant downward acceleration occurs	From velocity-time curve

Note: preliminary analysis determined that the first measure of 10deg·s^{-1}, as seen in Lee et al., (2018) represented an unrealistic break-point (forward fall), as participants oscillated between 5-15deg·s^{-1} until a consistent acceleration was seen above 10deg·s^{-1}. Therefore, the last instance of 10deg·s^{-1} before a consistent downward acceleration occurred was used. Moreover, covering a 90° range of motion during the NHE at 10deg·s^{-1} is a very slow descent (9 seconds) and appears a low threshold to base AVK on. Some subsequent measures were extracted from the data and analysed including RTA and AVK at the point of BTA.

N Newton, F_{peak} peak force, F_{left} left limb force, F_{right} right limb force, Nm Newton meters, T_{peak} peak torque, r moment arm length, Kg Kilogram, T_{norm} peak torque normalised to body mass, BPA break-point angle, ° degrees, BTA break-torque angle, NHE Nordic hamstring exercise, RTA relative trunk-to-thigh angle, θ_{thigh} thigh segment angle, θ_{trunk} trunk segment angle, d differential operator, θ_{knee} knee segment angle, t time, ROM range of motion, AVK Angular velocity of the knee joint, deg.s^{-1} degrees per second, fAcc first acceleration, deg·s^{-2} degrees per second squared, eAcc acceleration elbow, pAcc peak acceleration, pVelocity peak knee angular velocity, angle@last10deg·s^{-1} angle at the last instance of 10deg·s^{-1}.

3.2.3 Participants

A total of eighteen male (n=18) recreational rugby union players of various playing positions and experience were recruited (mean ± SD age 20 ± 3years, height 182 ± 6.7cm, and body mass 91.0 ± 47.4kg). All participants were recruited from the same University sports team to ensure data would be based on players with similar conditioning levels. Their anthropometric profiles aligned closely with published date for similar athlete cohorts. National U19 rugby union players (n=184) had a mean height of 179 ± 7cm, and body mass 84.2 ± 14kg (Vaz et al., 2021). Furthermore, elite rugby union forward players (n=80) averaged 186 ± 5cm in height and 104 ± 10kg in body mass, while backs (n=79) averaged 180 ± 4cm and 95 ± 9kg (Brazier et al., 2020). Elite male Premiership football players (n=24) also typically range around these measures, showing comparable stature (180 ± 5cm) and body mass (81 ± 8kg) (Hencken & White, 2006). This present sample's slightly higher mean body mass suggests strong applicability of the findings to football cohorts and other athlete groups typically represented in the NHE metrics and terminology research.

Rugby players were chosen due to the current high incidence of HSIs in the sport, representing up to 15% of all injuries sustained (Fuller et al., 2020). Moreover, rugby players who completed a Nordic eccentric exercise programme showed significantly improved eccentric hamstring strength (Alegre & Wales, 2021), smaller bilateral strength imbalances and reduced HSI incidence and severity, as evidenced by fewer training and match days lost (Chavarro-Nieto et al., 2023). The sample size of 18 is consistent with previous studies that have examined kinematic metrics of the NHE, such as those by Ditroilo, De Vito and Delahunt, (2013) and Alt et al., (2018), which utilised participant numbers ranging from 16-18. This study is explanatory, aiming to investigate correlations between kinematic metrics to develop a standardised list for assessing the NHE action, rather than determining performance or injury risk prediction. Employing a within-participants design with repeated measures, where participants serve as their own controls, justifies a smaller sample size (Charness et al., 2012; Guo et al., 2013). This design reduces between-participant variability, increases statistical power and enhances sensitivity to detect within-participant changes (Guo et al., 2013; Tirrell et al., 2018). Moreover, sports biomechanics research frequently operates with small sample sizes due to logistical constraints (Vagenas et al., 2018), and within-participangts designs help maximise quality data under these limitations, allowing for more reliable detection of effects (Souza Oliveira & Pirscoveanu, 2021; Vagenas et al., 2018).

All participants completed a personal injury and training history questionnaire, with all reporting having some previous training experience of the NHE. Collected injury history confirmed all participants to be medically cleared and not currently carrying an injury which would affect completion of the NHE trials. Exclusion criteria included any participants not medically cleared from disease or any person carrying a trunk or lower limb musculo-skeletal injury that would affect performance of the NHE. Participants were asked to abstain from strenuous exercise and the ingesting of caffeine or alcohol 48 hours prior to the testing. All participants were given the same verbal instructions for controlling NHE quality, and encouragement was provided throughout. The study was approved by the University's Ethics Committee (ER6176646) and all participants provided written informed consent to participate in the spirit of the Helsinki Declaration, after having all procedures explained to them.

3.2.4 Procedures

A standardised warm-up was performed by each participant prior to the trials, consisting of 3 minutes on a stationary bike and a series of dynamic movement including walking lunges, squats, and leg swings (sets of 10 repetitions). A warm-up set of 3 submaximal bilateral NHEs were performed prior to the maximal trials (1 set of 3 repetitions) per person. The rest period between each trial was long enough (6-10 seconds) to allow the participant to comfortably recover before the next maximal effort (Alt & Schmidt, 2021a). This duration aligns with typical rest intervals used in isokinetic and eccentric strength testing protocols (Alt et al., 2022; Alt & Schmidt, 2021a). Siddle et al., (2018) used rest durations of 10 seconds between maximal eccentric hamstring efforts to maintain performance consistency and limit fatigue effects. A scoping review by Alt et al., (2022) recommended that inter-repetition rest of >6s counteracts the accumulation of excessive muscle fatigue across trials and ensures the preservation of exercise quality. All participants had prior experience with resistance training and were familiar with the NHE, however had not received specific familiarisation with the testing procedures. Verbal instruction on NHE technique quality was given to all participants by the researcher. Participants assumed a kneeling position on the device with their ankles secured in place approximately superior to the lateral malleolus, 0.6m away from the lateral femoral epicondyle (**Figure 18**).

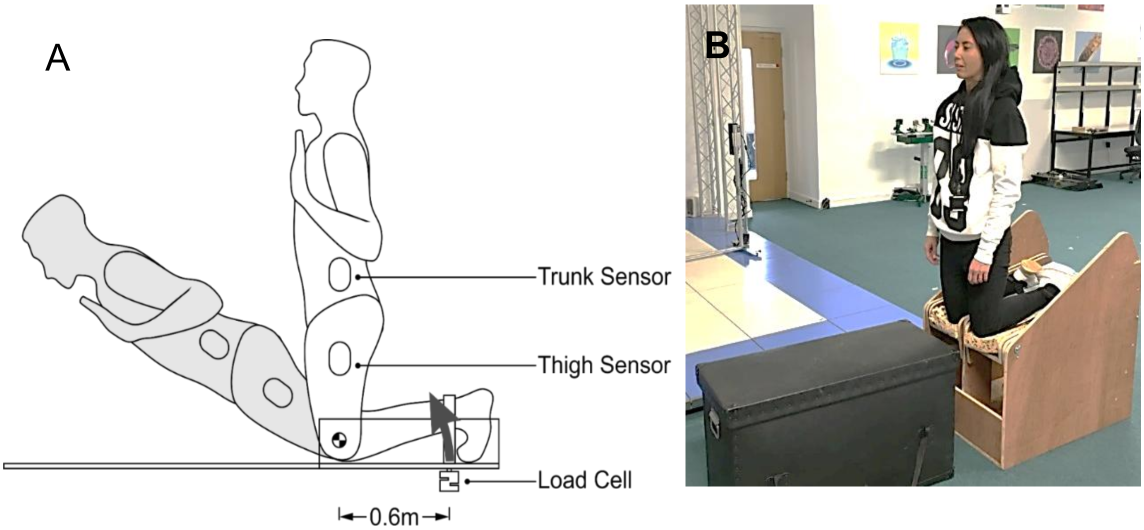


Figure 18: Panel (A) shows a computer-aided design model of the HALHAM° device, used to collect kinetic and kinematic metrics during Nordic hamstring exercise trials. Panel (B) illustrates an example of a participant performing the Nordic hamstring exercise on the HALHAM° device.

Participants started each trial in a fully extended hip and 90° knee position before commencing any forward movement. From this position each participant performed the NHE by a forward rotation about the knee. Participants were informed to gradually lean forward at the slowest possible speed, maximally resisting the movement with both legs, whilst holding the hips fixed in line with the knee and shoulder joints throughout the range of movement (Mjølsnes et al., 2004). The knee flexors provided the main resistance against gravity to control descent into the prone position. Participants were asked to keep hands facing forward and elbows pointing down, ready to buffer the fall. This action was performed until the participant could no longer withstand the torque around their knees caused by the increasing moment arm of their weight as they leaned forwards (Petersen et al., 2011; Sconce et al., 2015) (**Figure 18**). The load cells attached to the device produced force-time traces in line graph format, showing both individual right and left limb, and combined limb total forces. Torque was then calculated for each NHE trial from the force traces and the distance measured from the set pivot point to the centre of the ankle restraints (0.6m). To allow subsequent synchronisation of the load cells and Polhemus data sets, each participant was asked to tap the thigh sensor at the beginning of each NHE trial. The tap was detected as a sudden movement on the accelerometers and samples synchronously with the load cells. By manually identifying the tap signal on each trace the Polhemus system was synchronised.

The following kinetic metrics were derived from the load cell force-time traces:

- **Peak force** ~ NHE bilateral maximum force value.
- **Peak torque** ~ NHE bilateral maximum torque value.
- **Peak torque/kg** ~ NHE bilateral maximum torque value normalised to body mass

The following kinematic metric was derived from the high-speed camera and video analysis software:

- **Break-point angle (BPA)** ~ representing the angle at which visual loss of control occurred from the greater trochanter (hip) to the lateral femoral condyle (knee) relative to the horizontal.

The following kinematic metrics were derived from the Polhemus 3D motion capture system:

- **Break-torque angle (BTA)** ~ representing the definitive bilateral peak eccentric knee flexor torque value and its corresponding thigh angle.
- **Angular velocity of the knee joint (AVK)** ~ representing the angular velocity of the knee joint throughout the NHE range of motion, filtered using an 11-point average. Subsequently, AVK at BTA was extracted from the data.

- **Relative trunk-to-thigh angle (RTA)** ~ the angle between the thigh and the trunk throughout the NHE range of motion, relative to a fixed axis, representing hip angle. Subsequently, RTA at BTA angle was extracted from the data.
- **First angular acceleration point (fAcc)** ~ representing the first instance of significant angular acceleration on the acceleration-time curve, representing the initial loss of control in the NHE action.
- **The elbow point (eAcc)** ~ representing the inflection point on the acceleration time-curve representing the greatest release of NHE control.
- **Peak acceleration point (pAcc)** ~ representing the maximum angular acceleration value recorded.
- **Angles at fAcc, eAcc and pAcc (angle@fAcc, angle@eAcc, angle@pAcc)** ~ representing the corresponding knee joint angles at those acceleration points.
- **Peak velocity point (pVelocity)** ~ representing the maximum angular velocity of the knee joint value recorded.
- **Angle at peak velocity (angle@pVelocity)** ~ representing the knee joint angle at which peak velocity occurs.
- **Last instance of 10deg·s^{-1} (angle@last10deg·s^{-1})** ~ representing the knee joint angle where angular velocity equals 10deg·s^{-1} before continuous downward acceleration occurs.

To facilitate consistent comparisons with previously published NHE data, all angular metrics reported in other studies were re-calculated to a full-extension reference system, where 180° represented knee extension. This was achieved by identifying the original reference point used in each study (e.g. vertical = 0°/90° or horizontal 0°/90°) and applying a linear transformation to convert the angles to the 0-180° convention. For example, an angle reported as 30° from horizontal was recalculated as 150° relative to full extension.

3.2.5 Statistical analyses

54 conventionally performed NHE trials were considered for analysis. Any mistrials were discounted (n=6), including where any participants reached full extension resulting in the absence of a discernible break-point (participant 2), and the absence of a tap signal on the thigh sensor affecting the synchronisation process (participants 5 and 7). Peak torque was measured, and trials were rejected when there was no clear peak, an extended flattened period, or when there was no definite drop-off period (n=4) (participants 5 and 7). NHE angular metrics were calculated by using 90° as the vertical starting position and full knee extension as 180°. The data were statistically processed in GraphPad Prism 8.43 (GraphPad Software Inc). The Shapiro-Wilks test was used for testing of normality. Variables were found to be normally distributed ($p>0.05$), satisfying assumptions for parametric testing.

Relationships between angular metrics were examined using Pearson product-moment correlations, reported with correlation coefficient (r), degrees of freedom (df), and associated p values. Pearson's r was used to quantify both the strength of the correlation and as the effect size. The strength of the correlation was interpreted using the following criteria: $r=1$, perfect positive correlation; $0.7 \le r < 1$, strong positive correlation; $0.3 \le r < 0.7$ moderate positive correlation; $0 \le r < 0.3$, weak positive correlation; $r=0$, no correlation. Positive values indicate a direct relationship between variables, whereas negative values indicate an inverse relationship (Schober & Schwarte, 2018). Statistical significance was set at $p<0.05$ for all analyses. Results were reported as test statistics in the following format: (test statistic (df) = value, p = …, effect size = …).

Variability was reported for all relevant metrics to characterise the dispersion of the data around the central tendency, and for comparison with the literature, where thresholds or reference ranges have been established. In addition, interquartile ranges (IQR) were calculated to quantify the central 50% of the dataset, defined as the difference between the third quartile (the value below which 75% of the data falls) and the first quartile (the value below which 25% of the data set falls). The IQR was used as it gives a measure of variability that is less sensitive to the influence of extreme values than the standard deviation.

Furthermore, the coefficient of variation (CV%) was calculated for each variable using the standard **Equation 2**. There are no established thresholds for within session intra-individual variability, however in sport science literature a CV% of $\leq$10% is typically considered very good-excellent, 10-20% acceptable, and >20% poor (Grgic et al., 2020).

$$CV\% = \left(\frac{SD}{Mean}\right) \text{x } 100$$

Equation 2: Coefficient of variation

CV coefficient of variation, SD standard deviation, Mean average metric score.

3.3 Results

Descriptive statistics for each metric are shown in **Table 5** and reported as mean ± standard deviation. Within-session intra-individual variability for each metric, expressed as CV%, is reported in **Table 6**. Low CV% values indicate low trial-to trial variability, reflecting high within-session consistency of the measured metrics. Summary inspection of the data indicates that the lowest mean knee angle occurred at the angle@last10deg·s^{-1}, followed by angle@fAcc and BPA. BPA exhibited the strongest correlation with the angle@fAcc metric, $r(42)=0.87$, $p<0.001$, as shown in the correlation matrix (**Figure 19**). Break torque angle (BTA) occurred later in the NHE action and demonstrated the strongest correlation with angle@eAcc, $r(42)=0.85$, $p<0.001$ (**Figure 19**). Angle@pVelocity occurred, on average, 19.6° after BTA. Large variability was observed in both angular velocity of the knee joint (AVK) and relative trunk-to-thigh angle (RTA) at BTA, as indicated by the interquartile ranges. These are summarised in **Table 6** and **Figure 20**.

Table 5: Mean and standard deviation for each metric considered in the study. Variability and interquartile ranges also reported for every metric.

Metrics	Mean ± SD	Range (Min-Max)	IQR (Q1-Q3)
Kinetics			
Peak force (N)	249.4 ± 116.8	84.1 - 527.9	164.4 - 333.3
Peak torque (Nm)	149.7 ± 70.1	50.5 - 316.7	98.6 - 200.0
Peak torque/kg (Nm/kg)	1.6 ± 0.7	0.4 - 3.2	1.0 - 2.2
Kinematics			
BPA (°)	121.5 ± 10.4	103.0 - 145.0	113.0 - 130.0
BTA (°)	126.0 ± 9.8	108.8 - 149.4	117.8 - 131.5
AVK ($deg{\cdot}s^{-1}$) at BTA	29.2 ± 22.6	3.6 - 93.4	15.5 - 30.3
RTA (°) at BTA	16.7 ± 10.8	0.4 - 44.7	6.5 - 24.4
fAcc ($deg{\cdot}s^{-2}$)	21.1 ± 10.0	6.7 - 52.8	14.4 - 26.8
Angle@fAcc (°)	119.2 ± 7.1	108.1 - 134.3	112.9 - 125.2
eAcc ($deg{\cdot}s^{-2}$)	54.1 ± 27.8	21.0 - 121.9	34.1 - 76.9
Angle@eAcc (°)	123.9 ± 7.9	111.1 - 143.8	117.7 - 129.8
pAcc ($deg{\cdot}s^{-2}$)	222.5 ± 61.8	87.9 - 340.9	194.4 - 267.6
Angle@pAcc (°)	134.0 ± 7.6	121.8 - 150.7	128.2 - 140.0
Angle@last10$deg{\cdot}s^{-1}$ (°)	117.3 ± 6.8	103.9 - 129.4	111.7 - 123.5
pVelocity ($deg{\cdot}s^{-1}$)	101.0 ± 24.0	40.1 - 155.8	82.9 - 119.1
Angle@pVelocity (°)	145.6 ± 7.1	132.2 - 160.9	140.4 - 150.0

SD standard deviation, IQR interquartile range, N Newton, Nm Newton meters, Kg Kilogram, BPA break-point angle, ° degrees, BTA break-torque angle, AVK Angular velocity of the knee joint, $deg{\cdot}s^{-1}$ degrees per second, RTA relative trunk-to-thigh angle, fAcc first acceleration, $deg{\cdot}s^{-2}$ degrees per second squared, eAcc acceleration elbow, pAcc peak acceleration, angle@last10 $deg{\cdot}s^{-1}$ angle at the last instance of 10 $deg{\cdot}s^{-1}$, pVelocity peak knee angular velocity.

Table 6: Intra-reliability for each kinematic metric for every accepted trial (44) across all participants (n=15). Mean and standard deviation, and coefficient of variation values reported for all participants with accepted trials of 2 or more.

	KINEMATICS													
Participant	BPA (°)		BTA (°)		fAcc (deg·s^{-2})		Angle@fAcc (°)		eAcc (deg·s^{-2})		Angle@eAcc (°)		pAcc (deg·s^{-2})	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
1	125.0 ± 3.6	2.8	129.7 ± 4.7	3.6	23.3 ± 5.1	22.1	124.6 ± 2.4	1.9	59.7 ± 26.2	43.9	129.7 ± 2.6	2.0	233.3 ± 33.2	14.2
3	122.3 ± 2.1	1.7	128.4 ± 3.0	2.3	16.6 ± 3.2	19.2	124.6 ± 2.9	2.3	31.7 ± 8.2	25.8	127.4 ± 1.7	1.3	151.3 ± 98.7	65.3
4	117.7 ± 0.6	0.5	118.5 ± 2.5	2.1	17.4 ± 6.1	34.8	114.1 ± 2.2	1.9	40.6 ± 6.2	15.2	115.9 ± 1.6	1.4	224.0 ± 27.3	12.2
6	140.3 ± 5.0	3.6	147.7 ± 2.1	1.4	17.3 ± 8.2	47.5	130.7 ± 4.0	3.1	43.9 ± 22.2	50.5	139.7 ± 3.6	2.6	128.8 ± 34.8	27.0
8	124.0 ± 5.2	4.2	130.4 ± 1.7	1.3	13.2 ± 8.8	67.0	126.0 ± 2.5	2.0	41.9 ± 12.7	30.4	131.6 ± 3.2	2.4	187.6 ± 23.9	12.7
9	134.7 ± 5.5	4.1	128.9 ± 4.1	3.2	24.3 ± 5.2	21.6	125.4 ±2.7	2.2	56.2 ± 28.0	49.9	131.0 ± 3.2	2.4	313.8 ± 28.5	9.1
10	129.7 ± 1.5	1.2	126.8 ±1.5	1.2	21.0 ± 6.2	29.7	122.2 ± 0.6	0.5	39.2 ± 6.9	17.5	124.9 ± 1.5	1.2	175.5 ± 21.5	12.3
11	112.3 ± 1.2	1.0	119.9 ± 1.9	1.6	17.4 ± 4.3	24.4	116.7 ± 2.6	2.3	111.9 ± 10.1	9.1	122.2 ± 2.7	2.2	231.9 ± 23.5	10.2
12	112.0 ± 1.0	0.9	128.9 ± 1.0	0.8	22.5 ± 7.9	35.3	110.9 ± 0.9	0.9	88.8 ± 17.3	19.5	120.7 ± 0.7	0.6	224.8 ± 18.6	8.3
13	135.3 ± 3.2	2.4	136.7 ± 6.9	5.0	19.1 ± 11.6	60.9	127.3 ± 4.1	3.2	33.9 ± 19.8	58.5	130.9 ± 3.3	2.5	164.9 ± 32.4	19.6
14	119.7 ± 1.5	1.3	119.8 ± 2.2	1.8	18.1 ± 9.3	51.6	113.5 ± 0.9	0.8	48.2 ± 10.9	22.5	119.7 ± 0.4	0.3	239.3 ± 19.5	8.2
15§	110.0 ± 4.2	3.9	118.6 ± 5.4	4.6	45.1 ± 10.9	24.2	112.7 ± 0.2	0.2	57.3 ± 33.1	57.8	116.2 ± 1.6	1.4	275.2 ± 30.0	10.9
16	105.3 ± 2.1	2.0	111.3 ± 2.8	2.5	29.7 ± 12.7	42.8	110.2 ± 2.7	2.4	71.2 ± 36.7	51.5	113.2 ± 3.6	3.2	286.0 ± 27.1	9.5
17§	120.5 ±4.9	4.1	135.4 ± 2.4	1.8	20.7 ± 6.3	30.2	115.9 ± 1.3	1.1	55.4 ± 15.9	28.6	120.7 ± 0.5	0.4	199.1 ± 5.3	2.7
18	113.3 ± 0.6	0.5	112.6 ± 0.5	0.4	11.0 ± 3.3	30.2	111.5 ± 0.6	0.6	24.7 ± 0.9	3.5	112.7 ± 0.6	0.6	293.2 ± 36.5	12.5

KINEMATICS												
Participant	Angle@pAcc (°)		Angle@last10deg·s^{-1}(°)		pVelocity (deg·s^{-1})		Angle@pVelocity (°)		AVK (deg·s^{-1}) at BTA		RTA (°) at BTA	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
1	139.2 ± 2.6	1.8	120.5 ± 1.7	1.4	99.9 ± 5.6	5.6	150.0 ± 1.2	0.8	24.8 ± 6.4	25.9	25.5 ± 6.0	23.6
3	132.5 ± 2.9	2.2	123.8 ± 2.3	1.9	48.6 ± 9.6	19.8	138.4 ± 4.5	3.2	19.6 ± 6.5	33.1	39.6 ± 4.4	11.2
4	124.4 ± 3.1	2.5	109.6 ± 1.1	1.0	93.0 ± 11.9	12.8	136.7 ± 4.5	3.3	25.7 ± 9.7	37.7	26.6 ± 2.6	9.8
6	147.2 ± 3.2	2.1	122.9 ± 5.4	4.4	75.4 ± 10.1	13.5	156.3 ± 3.5	2.2	47.5 ± 18.7	39.4	25.9 ± 2.2	8.3
8	140.2 ± 1.5	1.1	118.0 ± 12.2	10.3	92.0 ± 1.0	1.1	149.3 ± 1.6	1.1	18.8 ± 2.9	15.3	15.7 ± 2.3	15.0
9	142.1 ± 5.0	3.5	125.1 ± 1.9	1.6	135.9 ± 18.2	13.4	157.0 ± 5.4	3.4	18.7 ± 8.1	43.2	5.2 ± 5.0	96.5
10	136.7 ± 7.6	5.6	122.3 ± 1.4	1.1	79.3 ± 3.0	3.8	144.9 ± 3.9	2.7	18.4 ± 8.6	46.9	24.7 ± 3.1	12.5
11	132.6 ± 2.7	2.0	115.2 ± 3.1	2.7	117.3 ± 12.8	10.9	145.5 ± 2.4	1.7	20.7 ± 6.9	33.1	15.3 ± 8.0	51.9
12	132.9 ± 2.7	2.0	110.7 ± 1.8	1.6	121.7 ± 5.1	4.2	147.2 ± 2.7	1.8	74.0 ± 26.3	35.6	8.2 ± 6.2	76.3
13	140.7 ± 3.8	2.7	127.1 ± 2.1	1.6	84.9 ± 10.0	11.7	150.1 ± 2.2	1.5	38.9 ± 24.8	63.8	11.5 ±10.4	90.5
14	130.1 ± 1.0	0.8	113.2 ± 1.0	0.9	103.9 ± 8.7	8.4	145.3 ± 1.3	0.9	26.2 ± 5.1	19.4	4.6 ± 4.2	91.8
15§	123.7 ± 0.2	0.2	106.5 ± 0.7	0.7	106.3 ± 3.0	2.9	135.8 ± 0.8	0.6	40.0 ± 20.0	49.9	12.8 ± 9.6	75.2
16	125.4 ± 0.7	0.6	111.8 ± 2.5	2.2	127.5 ± 9.3	7.3	140.4 ± 1.1	0.8	7.4 ± 2.4	33.2	15.8 ± 4.3	26.9
17§	135.1 ± 1.1	0.8	117.3 ± 0.3	0.3	110.7 ± 0.9	0.9	149.7 ± 0.9	0.6	91.1 ± 3.2	3.5	5.5 ± 0.6	11.0
18	124.2 ± 2.1	1.7	113.4 ± 0.6	0.5	117.7 ± 11.3	9.6	135.6 ± 4.2	3.1	5.8 ± 2.1	36.5	14.0 ± 2.6	18.9

§No clear tap signal for synchronisation of systems

BPA break-point angle, ° degrees, BTA break-torque angle, fAcc first acceleration, deg·s^{-2} degrees per second squared, eAcc acceleration elbow, pAcc peak acceleration, SD standard deviation, CV coefficient of variation, angle@last10 deg·s^{-1} angle at the last instance of 10 deg·s^{-1}, pVelocity peak knee angular velocity, deg.s^{-1} degrees per second, RTA relative trunk-to-thigh angle, AVK Angular velocity of the knee joint.

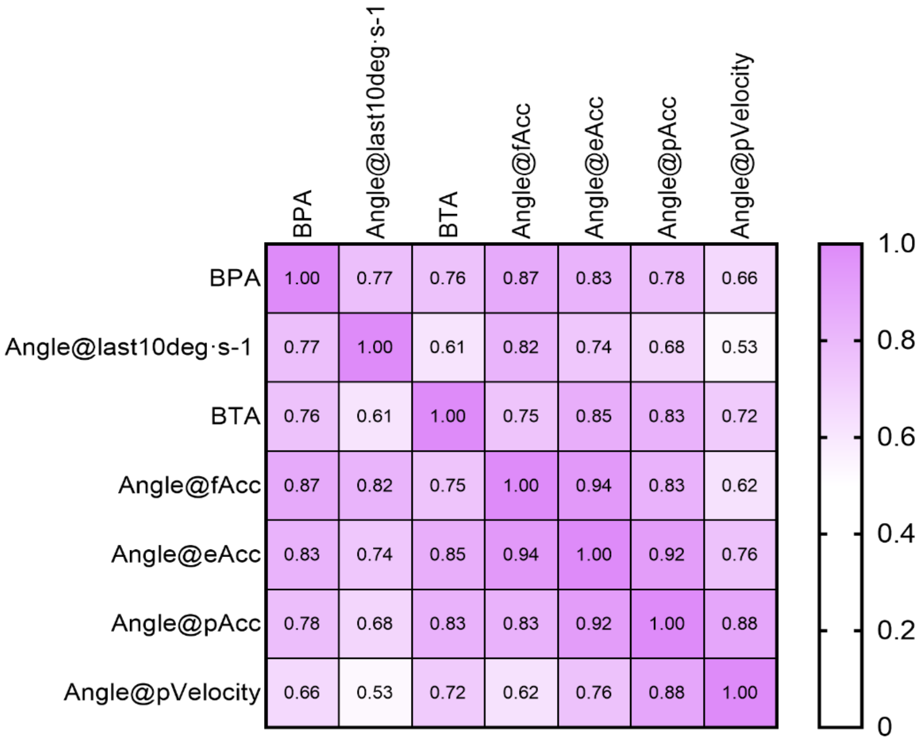


Figure 19: Correlation matrix showing Pearson correlation coefficients (r) between angular kinematic metrics used to explore the NHE action. All metrics show statistical significance defined as p<0.05.

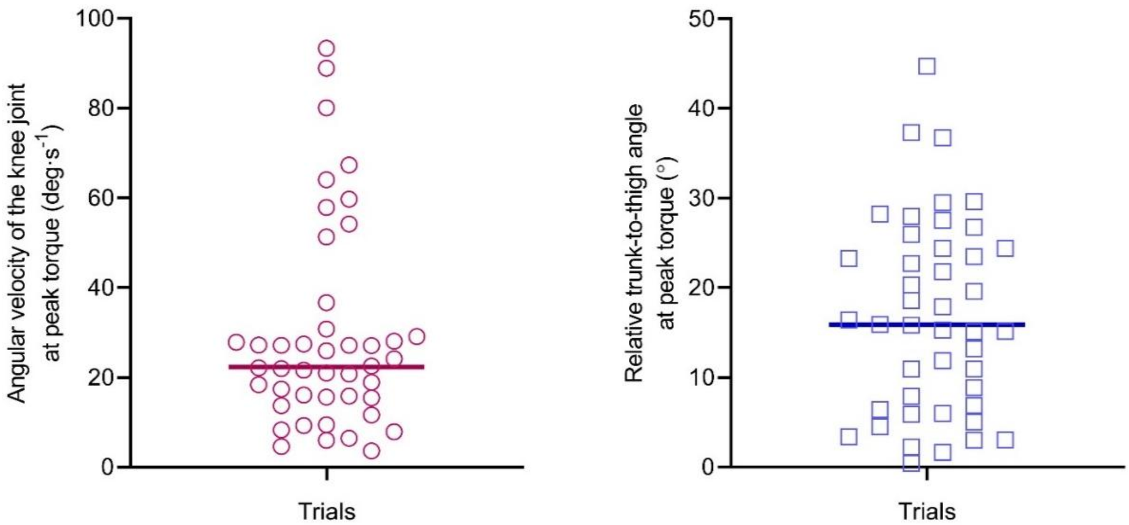


Figure 20: Scatter plots showing the individual data points (n=44) for angular velocity of the knee joint and relative trunk-to-thigh angle, at peak torque. Wide variability can be seen in the data for both metrics, highlighting Nordic hamstring exercise technique differences in individuals.

3.4 Discussion

Consistent with the gaps identified in the literature this study assessed multiple kinetic and kinematic metrics during the NHE to determine their utility in describing performance neuromuscular control accurately and consistently. By concurrently measuring force, angles, velocities, and relative joint position using the HA*L*HAM°, the analysis aimed to identify which metrics most consistently reflect eccentric hamstring function and control. This approach provides a framework for interpreting NHE performance beyond traditional single metrics and helps address inconsistencies in previous research methods. Although BPA, BTA, CUHK Nordic break-point test and angle at DWA are similar metrics, they have all been measured differently in the literature, both by method and definition, making comparison to the reported results in this study difficult (**Table 3** and **Table 5**). The primary finding of this study is the high within-session consistency for BTA, evidenced by low CV values (**Table 6**), reflecting low variability across trials and supporting its use as a repeatable metric. BTA can be considered a well-defined metric because it is objectively derived from torque-angle data and does not relay on arbitrary thresholds, unlike other kinematic measures that require identifying a specific velocity threshold or time-point. This makes the BTA less susceptible to variation introduced by individual differences in descent technique or inconsistencies in execution. In contrast, measures such as BPA or angle@pVelocity are more strongly influenced by technical factors (e.g. premature braking, arm bracing or descent speed), which can increase variability and reduce consistency as markers of eccentric performance. Importantly, the functional relevance of the BTA lies in its ability to provide meaningful insight into proxy changes in muscle length, by quantifying the angle that peak torque can be produced. This is relevant for injury prevention and rehabilitation, since the ability to generate high torque at extended muscle lengths is associated with reduced susceptibly to HSIs and more effective recovery, supporting faster return-to-play outcomes (Guex et al., 2016; Marušič et al., 2020; Tyler et al., 2017). The low CVs observed for BTA further highlight its potential as a metric with low trial-to-trial variability, supporting its use as a standardised and consistent outcome measure for assessing NHE performance.

The relatively high CVs for the exercise technique metrics of AVK at BTA (3.5% to 63.8%) and RTA at BTA (8.3% to 96.5%) highlight their sensitivity to variations in exercise execution. Despite this, their inclusion remains valid for subsequent studies, as both metrics provide valuable, complementary insight into exercise quality differences. By capturing how descent speed and hip flexion fluctuate between participants, AVK and RTA and BTA contextualises how technique may influence performance outcomes.

Throughout this discussion, angular results from previous studies have been re-calculated to a full-extension reference system (180°=full knee extension) as described in the procedures, to enable consistent comparisons with the current data. BPA, BTA, CUHK Nordic break-point test and angle at DWA Mean ± SD (139 ± 8.1°;107.76 ± 8.1°;130.78 ± 8.1°;111.9 ± 8.0°;103.1 ± 3.8°) shows variability between studies in the literature and differs to BPA, BTA, and angle@last10deg·s^{-1} in this study (121.5 ± 10.4°;126.0 ± 9.8°;117.3 ± 6.8°). However, angle of pVelocity results (145.6 ± 7.1°) showed consistency with the literature when calculated to full extension = 180° (138.2 ± 5.6°; 142.3°) (Delahunt et al., 2016; McGrath et al., 2020). Kinematic studies are limited in number and present differences in participant ability (elite/recreational), gender, training experience and NHE familiarisation, so discrepancies between studies are to be expected. A consolidated list of kinematic metrics than can be used to assess each part of the NHE action to assist a standardised approach in future research can be seen in **Table 4.** The mean relative knee angle reported for each angular metric provides some useful commentary as to the sequence of the NHE action, however technique needs to be considered when discussing the validity of these metrics. Angle@last10deg·s^{-1} shows the closest association to angle@fAcc however there was a large variation in acceleration reported at fAcc (6.7-52.8deg·s^{-2}), unrelatable to 10deg·s^{-1}. This could be indicative of difference in technique where some individuals were able to descend gradually at the start of the NHE, whilst others demonstrated a more uncontrolled acceleration and a less effective 'hold' before 'breaking'. IQRs for fAcc suggest a baseline and threshold of 14.4-26.8deg·s^{-2} to be considered for instance of first acceleration (**Table 5**).

Most studies to date have not considered exercise quality through kinematic feedback. Bourne et al. (2019) states that a NHE trial is deemed acceptable when the force output reaches a distinct peak (indicative of maximal eccentric strength), followed by a rapid decline in force, occurring when the participant can no longer resist the effects of gravity and therefore trials were discounted if no peak was evident. An improvement in NHE performance (how well the participant delays the 'break' of the fall) was found by Delahunt et al. (2016) after a 6-week eccentric training intervention. A longer control of the forward fall component of the NHE/smaller angle at DWA (where full extension=0°) was reported (73.7° vs. 68.1°, p=0.022, d=0.90). Therefore, NHE training should improve an individual's ability to reach a lower NHE position and thus a larger BTA. A distinct torque drop-off period, representative of an obvious release of control should be evident, as it has importance in ensuring a supramaximal, distinct break-point and subsequently determining an accurate BTA. BTA could theoretically be an important metric to assess *proxy* muscle length changes i.e. the angular range over which the torque can be produced within the hamstrings. It is an indicator of the trade-off point (torque-muscle length) at which hamstring muscle failure ensues, providing a more specific metric relative to the proposed injury mechanism at which HSIs occur during high-speed running.

Most studies reported hip flexion to start fully extended at the beginning of the NHE movement (0°) (Ditroilo et al., 2013; Lee et al., 2017; Pollard et al., 2019) and then remain extended throughout, rejecting any trials with 'over-excessive hip flexion' (Muggleton, 2015). However, this was nearly always measured via visual inspection rather than by objective measurement of hip angle. In this study, participants were instructed to maintain full extension during a slow approach, which was monitored visually in real-time. Importantly, objective kinematic metrics were collected, including angular velocity of the knee joint (reflecting descent speed) and relative trunk-to-thigh angle (reflecting hip flexion). These measures allowed post-hoc, quantitative assessment of technique, providing a more precise evaluation of movement than visual inspection alone and enabling identification of variations in descent speed or hip position that may not be apparent in real-time. Future work will be required to more effectively regulate descent speed across participants, as indicated by the large variability in AVK at BTA (3.6-93.4 $deg \cdot s^{-1}$), the widespread of acceleration values (6.7-52.8$deg \cdot s^{-2}$) and the range of RTA at BTA values (0.4-44.7°). These findings suggest substantial individual differences in descent technique during the NHE in this study (**Table 5** and **Figure 20**).

Alt et al. (2018) reported a similar mean hip flexion for unassisted NHE trials (17.0 ± 8.2° vs. 16.7 ± 10.8°), however, technique proved problematic to control and enforce between participants in this study due to varied individual techniques, and a lack of previous familiarisation, which may go some way to explaining the high intrasubject variability of RTA and AVK at BTA. The primary limitation of this study was the lack of familiarisation with the testing procedures and specific NHE technique prior to kinematic testing, which contributed to suboptimal exercise execution. Although verbal instructions were provided, the findings suggest that verbal guidance alone is insufficient to achieve the intended exercise quality. It is proposed that trunk flexion should be controlled more stringently using real-time kinematic feedback as studies have shown that greater hip flexion during the NHE can produce larger torque values at the same knee angle compared to a standard hip position (Hegyi et al., 2019; Šarabon et al., 2019). This is due to the increased lever arm of the centre of mass about the knee joint axis increasing the resultant torque (Hegyi et al., 2019; Šarabon et al., 2019). Employing a controlled neutral hip flexion technique is likely preferential for greater fascicle lengthening and maximising hypertrophy in the BFLH (Raiteri et al., 2021; Timmins, Bourne, et al., 2016) as there is less involvement from the accessory muscles such as the gluteus maximus and erector spinae (Sconce et al., 2021b). These adaptations are desired for their protective qualities in the prevention of HSIs (Timmins, Bourne, et al., 2016). Furthermore, as suggested by Alt & Schmidt, (2021a) poor NHE execution may impede or even prevent adaptations at long hamstring muscle lengths occurring at extended angles.

Heterogeneous groups have been used throughout the research, illustrating differences in participant training experience and level of NHE familiarisation. Ditroilo et al. (2013) used recreational participants whilst Lee et al., (2017, 2018) and McGrath et al. (2020) tested semi-professional players. McGrath et al. (2020) performed single-leg NHE testing, indicating those athletes to be very highly trained. Differences in exercise mode (unilateral/bilateral), training experience, and NHE familiarisation combined with non-standardised measurement (hip angle, movement speed, distinct peak torque and drop-off) affects technique (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Lee et al., 2017, 2018; Šarabon et al., 2019; Sconce et al., 2015) and may have influenced kinetic and kinematic values (torque, angular velocity). Moreover, the range of motion in which pVelocity and pAcc occur during the NHE is in the time-period after 'break' where inter-subject differences in landing method are likely to influence output measures. Participants were instructed to keep their hands facing forward and elbows pointing down, ready to buffer the fall. Those losing control nearer vertical have potentially more ROM in which to increase velocity. However, those breaking early tended to buffer the fall with further outstretched arms (contrary to instructions) limiting the ROM over which velocity can be generated, which is a recognised limitation of this study and when using these types of measures. Intervention or performance studies often exclude such data to assess efficacy under controlled conditions; however, these trials were included in the data because this was an exploratory study aimed at identifying which kinetic and kinematic metrics best capture the NHE action and can be reproduced with low variability. Including all observed variations in technique, even those deviating from verbal instruction, was appropriate in this context, as the aim was to understand the full NHE movement patterns and their impact on metrics.

3.5 Conclusion

This chapter has systematically compared methods and metrics used to assess the NHE and proposes standardised terminology and metric definitions grounded in the reported data. Metrics were selected based on three key findings:

i. Metrics with low trial-to-trial variability (i.e. BTA) were identified as consistent and suitable for reproducible monitoring of NHE performance.
ii. BTA represents the proxy length in the hamstring at which muscle failure occurs. The focus should not just be on hamstring strength maintenance but on torque production over a greater muscle length, replicating more closely the common injury site location during the late-swing sprinting phase.

iii. Kinematic exercise quality measures such as RTA (hip flexion) and AVK (descent speed) at BTA revealed high variability across participants, highlighting the need for explicit definitions of technique-related terms to standardise reporting.

Correlation analysis between angular torque metrics and traditional metrics used currently (e.g. peak force/torque) supported by the selection of BTA as a functional interpretable outcome, because it consistently reflected eccentric hamstring function across participants while being less sensitive to individual technique differences. The variability data further guided the distinction between robust metrics (low CV) and technique-sensitive metrics (high CV), which informed the proposed standardised terminology for NHE assessment.

The HA*L*HAM° provides a platform for simultaneous kinetic and kinematic measurement, allowing both performance and technique variability to be quantified. Metrics with low variability can be used reliably in the field for monitoring eccentric hamstring performance, while technique-sensitive metrics should be reported to interpret potential confounding factors in performance outcomes. Future research should continue to refine feedback methods and control for exercise quality, as large variability in descent speed and hip flexion was observed, which can influence the interpretation of kinetic outcomes. Overall, the proposed standardised terms and metrics are directly supported by the reported date, linking variability correlations and functional relevance to support reproducible and meaningful NHE assessment.

3.6 Chapter conclusion statement

This chapter proposed data-driven standardised methods and terminology to define NHE performance, based on the reported variability and correlations between metrics. Simultaneous measurement of kinetics and kinematics on the HA*L*HAM° is recommended to determine BTA, representing the proxy length at which hamstring muscle failure occurs and reflecting the proposed injury mechanism during high-speed running. Future research should consider movement quality, as large variability was observed for both descent speed and hip flexion, which can influence NHE performance outcomes.

Chapter 4

Study 2 – Modifying and Measuring the Knee Flexors' Torque-Length Relationship Using the HA*L*HAM°

Elements of this chapter have been published in the article titled, "Development of a novel Nordic hamstring exercise device to measure and modify the knee flexors' torque-length relationship'" in *Frontiers in Sports and Active Living* (https://doi.org/10.3389/fspor.2021.629606).

This chapter investigates the use of the HA*L*HAM° device to measure and modify the NHE torque-length relationship of the knee flexors, as targeting the hamstrings at a more extended length may have benefits for HSI prevention and rehabilitation. Agreed NHE performance and technique metrics from **Chapter 3** will be applied to the methodology design of the study.

4.1 Chapter aim

The aim of this chapter was to use the HA*L*HAM° device to assess the kinetic and kinematic effects of performing the NHE at different inclines on the torque-length relationship of the knee flexors.

4.1.1 Study objectives

i. Investigate the effects of flat and inclined NHE conditions on torque-angle characteristics using the HA*L*HAM° device.

ii. Determine whether the incline NHE shifts the torque-length relationship toward longer muscle lengths.

4.1.2 Hypothesis

i. Compared to the flat NHE, performing the NHE on an incline will shift the torque-length relationship rightward toward longer muscle lengths, while maintaining comparable torque output.

4.2 Introduction

Some existing hamstring devices only measure linear force output and not torque about the knee, making measures unrelatable between players of different sizes. Moreover, they do not measure angular range over which the force can be produced. Such a relationship between joint angle and muscle length is important as previously injured muscles reach peak torque at significantly shorter lengths (40.9° ± 2.7°) than uninjured muscles of the opposite leg (29.8° ± 1.5° where 0°=full extension) (Brockett et al., 2004). A number of commercial devices have adapted the NHE by altering declination to minimize knee hyperextension or allow assistance to make the NHE easier to perform (Lodge et al., 2020). Other devices are assisted (Alt et al., 2018; Giacomo et al., 2018), which compromises the pure eccentric nature of the NHE, and removes the ability to achieve supramaximal intensity, which may limit its effectiveness as an injury prevention exercise. In Ditroilo et al., (2013) the mean angle at which participants lost eccentric control during a standard NHE occurred until a downward acceleration of 68.1° ± 8.0° (with 90° being the kneeling start position), meaning most participants only utilised less than a third of the range of motion available. A full range of motion produces the greatest increases in strength at a long muscle length, while partial range of motion exercise produces the greatest increases in strength at a more moderate muscle length (Guex et al., 2016; Maeo et al., 2021; Marušič et al., 2020; Tyler et al., 2017; Van Hooren et al., 2022). It appears necessary to consider assistant systems that permit a larger ROM to be utilised during the NHE, potentially increasing the validity of desired metrics, and reducing potential bias when interpreting training adaptations or rehabilitation outcomes (Wiesinger et al., 2020). For instance, avoiding the overestimation of strength gains or underestimation of injury risk when athletes train only through a partial ROM.

To address limitations in existing methods of measuring the torque-length relationship of the knee flexors, the HA*L*HAM° device was developed (Sconce et al., 2021a). The aim of this study was to facilitate performance of the NHE at different inclines, thereby enabling investigation of torque production across a broader range of muscle lengths than isn't possible with the conventional flat NHE. By aligning the knee joint axis with pivot point of the rig and capturing torque through strain gauge load cells (Omega, Engineering Inc. Norwalk, USA), the HA*L*HAM° provides a controlled way of quantifying the torque-length relationship. Unilateral testing is possible on the HA*L*HAM° by securing only the testing limb into the ankle brace, however no unilateral NHE testing was performed due to the lack of familiarization of this exercise with the participants being tested.

The HA*L*HAM° offers a method beyond descriptive or visual assessment of the NHE, enabling objective evaluation of hamstring torque at extended muscle lengths, which has positive implications for injury rehabilitation and rehabilitation return to-play outcomes (Guex et al., 2016; Maeo et al., 2021; Marušič et al., 2020; Šarabon et al., 2019; Tyler et al., 2017). A study by Šarabon et al., (2019) strengthens the hypothesis that performing the NHE on an incline will allow a participant to exercise at longer muscle lengths, whilst still being able to reach supramaximal torques. They reported that participants were able to reach similar peak knee, and hip torques at longer estimated hamstring lengths, using NHE slopes of 20° and 40°. An NHE incline should result in a greater break-point angle, as the knee flexors are stretched over a longer range of motion compared to a flat Nordic. This increased muscle length may stimulate adaptations in fascicle length to optimise force generation at a longer length which is beneficial for HSI prevention (Khairunnisa et al., 2023; Park et al., 2019; Šarabon et al., 2019; Timmins, Bourne, et al., 2016; Van Hooren et al., 2022). A greater break-point angle (theoretically achieved by an incline NHE) means peak BF_{LH} activation should be preferentially attained at a more favourable longer length in the proximal hamstring range. A recent study by Soga, Hakariya, et al., (2023) supports this theory, demonstrating that incline NHE testing resulted in sustained high activation of the BF_{LH} while reducing ST activation compared to the flat Nordic variation. In individuals with a history of HSI, a muscle recruitment pattern that produced more symmetrical activation between the BFLH and ST was associated with less efficient hamstring activation, meaning that the muscles required more effort to produce the same force (Schuermans et al., 2014). This suggests that injury to the BF_{LH} may occur because it is not optimally suited for force production in the shorter, proximal range of motion. By preferentially recruiting the BF_{LH} at a longer muscle length, and managing the interplay between the BF_{LH}-ST, this could be beneficial for injury prevention and rehabilitation outcomes.

4.3 Methods

Research findings indicate that consistent NHE training incorporating low repetitions can lead to an increase in the angle of peak torque, and therefore BPA should increase (Cuthbert et al., 2020b). It is hypothesized that an increased BPA over time may be the intensity stimulus needed to maintain greater knee flexor adaptations (Cuthbert et al., 2020a), supporting the notion of it being a useful metric to monitor within HSI prevention. The HA*L*HAM° measures knee angle at the break-point and torque about the knee. Previous work (**Chapter 3**) revealed '*BTA'* to be a key kinematic measure (representing the peak torque value and its corresponding relative thigh angle at that point). The HA*L*HAM° used BTA as an indirect indicator of *proxy* muscle length changes, utilising an adjustable inclination mechanism that allowed the starting knee angle of the NHE to be increased by 10°.

The HA*L*HAM° device consisted of a flat platform with ankle straps positioned 0.6m from the pivot point at the front of the rig. This determined the NHE start position, lining up the lateral femoral epicondyle of the femur with the pivot point before commencement. Torque was calculated from the strain gauge load cells (Omega, Engineering Inc. Norwalk, USA) attached at the rear in a fixed position, mounted in a moveable tray parallel to the shank, with the platform tray free to rotate. All testing was performed bilaterally. A laboratory grade 3-dimensional electromagnetic motion tracking system (Liberty® Polhemus, Colchester, Vermont, USA) was used to quantify angular displacement of the thigh and trunk during the NHE. The system operated by emitting low-frequency electromagnetic fields from a transmitter, which were detected by lightweight sensors attached to specific anatomical landmarks. Based on the relative positive and orientation of the sensors, the system calculated joint kinematics, providing continuous high-resolution data on angular displacement throughout the movement. This method was selected because electromagnetic tracking provides sub-millimetre accuracy, does not require line-of-sight (unlike optical camera systems), and is less susceptible to skin movement artefact compared to surface markers tracked by video analysis. These characteristics make it particularly well-suited for measuring dynamic movements like the NHE, where precision and reliability of angular data are important. The thigh sensor was positioned laterally on the upper leg equidistant from the greater trochanter and lateral femoral epicondyle. The trunk sensor was also positioned laterally equidistant from the greater trochanter and the shoulder bursa. Polhemus Liberty® software was used to collect kinematic data from the two sensors sampled at 240Hz. Load cell data were sampled at 125Hz via a Phidget Bridge data acquisition board (Phidgets Inc., Calgary, Canada) and exported in .CSV format to be processed on a personal computer. Further analysis was performed in spreadsheet software (Microsoft Excel software, Microsoft Corp., Redmond, Washington). Ethical approval for the study was approved by the Sheffield Hallam University Ethics Committee (ER8248681).

Calculated parameters included:

- **Break-torque angle (BTA)** ~ representing the definitive bilateral peak eccentric knee flexor torque value and its corresponding thigh angle.
- **Peak torque** ~ NHE bilateral maximum torque value.
- **Relative trunk-to-thigh angle (RTA)** ~ the angle between the thigh and the trunk throughout the NHE range of motion, relative to a fixed axis, representing hip angle. Subsequently, RTA at BTA angle was extracted from the data.
- **Angular velocity of the knee joint (AVK)** ~ representing the angular velocity of the knee joint throughout the NHE range of motion, filtered using an 11-point average. Subsequently, AVK at BTA was extracted from the data.

These metrics were selected based on their physiological relevance, reliability, reproducibility, and sensitivity to key NHE performance characteristics, as established in **Chapter 3.** Peak torque and BTA were chosen for their capacity to quantify maximal eccentric knee loading at proxy muscle length. Device reliability studies on both the NordBord and Hamstring Solo have demonstrated high reliability for force measurements. Specifically, the NordBord has shown excellent test-retest reliability, with ICCs ranging from 0.993 (95% CI 0.983-0.997) for the left leg to 0.992 (95% CI 0.979-0.997) for the right leg (Ogborn et al., 2021). Similarly, the Hamstring Solo has exhibited moderate-to-high reliability, with ICCs between 0.83 and 0.90 for force measurements, and high test-retest reliability (ICC=0.910-0.914) (Lodge et al., 2020). These findings indicate that commercially available hamstring devices can reliably capture eccentric force metrics. The HA*L*HAM° load cells were calibrated to ensure accurate measurement of eccentric knee torque. In **Chapter 3**, BTA exhibited low CV (0.4-5.0%), supporting its use as a reproducible metric.

Conversely, RTA and AVK at BTA displayed high variability (8.3-96.5%) reflecting their sensitivity to individual exercise technique differences rather than poor measurement reliability. They were included to provide complementary information on exercise execution and inter-trial variability, helping to contextualise differences in performance outcomes.

4.3.3 Participants

Females were excluded to control physiological differences between sexes and because male soccer players are 64% more likely to sustain an HSI and suffer a higher proportion of recurrent HSIs compared with females (men 22% vs. women 12%) (Cross et al., 2013). Eighteen recreationally active male rugby union players (n=18) of varying playing experience were recruited to participate in this study (mean ± SD age 20 ± 3years, height 182 ± 6.7cm, and body mass 91.0 ± 47.4kg). HSIs are a current significant concern in rugby. Notably, during the Rugby World Cup in 2019, HSIs were the second most prevalent injury sustained during matches trailing only behind concussion (Fuller et al., 2020). These injuries accounted for half (50%) of all missed training or playing days showing the substantial impact of HSIs on player availability and performance (Fuller et al., 2020). The sample size of 18 was considered sufficient based on the only comparable recent study evaluating variations of the NHE by altering the slope of the lower leg. Šarabon et al., (2019) calculated that a minimal sample size of 15 participants was required to achieve a 80% statistical power, with an alpha of 0.05 and an anticipated effect size of 0.5. This effect size represents a moderate effect, which aligns with the expected magnitude of change in torque-length when manipulating NHE slope. Therefore, the current study was adequately powered to detect meaningful differences in the key outcomes.

Participants completed a questionnaire, used to gather injury data and personal characteristics. All participants reported having some previous training history of performing the NHE. Two participants reported a previous Grade 1 thigh muscle injury in the last 6 months but were stated as being physically fit and not currently carrying an injury which would affect them completing the NHE trials. All other participants had no lower-limb injuries reported in the last 12 months. Exclusion criterion included any participants not medically cleared from disease or any person carrying an injury that would affect performance of the NHE. Participants were recruited from the same sport and team level to ensure gathered data would be based on players with similar conditioning levels. After having all procedures explained to them, participants provided written informed consent to participate in the spirit of the Helsinki Declaration, before testing commenced. Prior to performing the trials participants were instructed to perform a standardised warm-up by using a stationary bike for 3 minutes and completing dynamic movements such as leg swings, walking lunges and squats (2 sets of 10 repetitions).

4.3.4 Procedures

Participants assumed a starting 90° kneeling position on the HA*L*HAM° device with their hips fully extended and their ankles were secured in place. Participants were asked to tap the thigh sensor at the beginning of each NHE trial and then gradually lean forward at the slowest possible speed, keeping their hips fixed in line with their knee and shoulder joints throughout the range of motion. They were instructed to keep their trunk in a neutral position throughout, with hands facing forward and elbows pointing down, ready to buffer the fall (Mjølsnes et al., 2004). This action was performed until the participant could no longer withstand the torque around their knees caused by the increasing moment arm of their mass as they leaned forwards (Petersen et al., 2011; Sconce et al., 2015).

A warm-up set of 3 submaximal bilateral NHEs were performed prior to 1 set of 3 maximal bilateral NHEs at a standard 0° flat angle position (FLAT), a 10° incline (INC) and a 10° decline angle (DEC). 9 trials per person were collected with each participant performing a set of 3 reps at one inclination before resting for 2-5 minutes until all 3 inclinations had been performed. The inclination order was randomized between participants. The rest period between reps was long enough to allow the participant to comfortably re-set themselves for the next maximal effort. Verbal encouragement was given by researchers throughout the testing to ensure maximal effort. 162 trials from 18 participants were initially considered for eligibility, resulting in 35 being excluded. The process of trial selection and the number of trials excluded at each stage, with reasons for rejection can be seen in **Figure 21**.

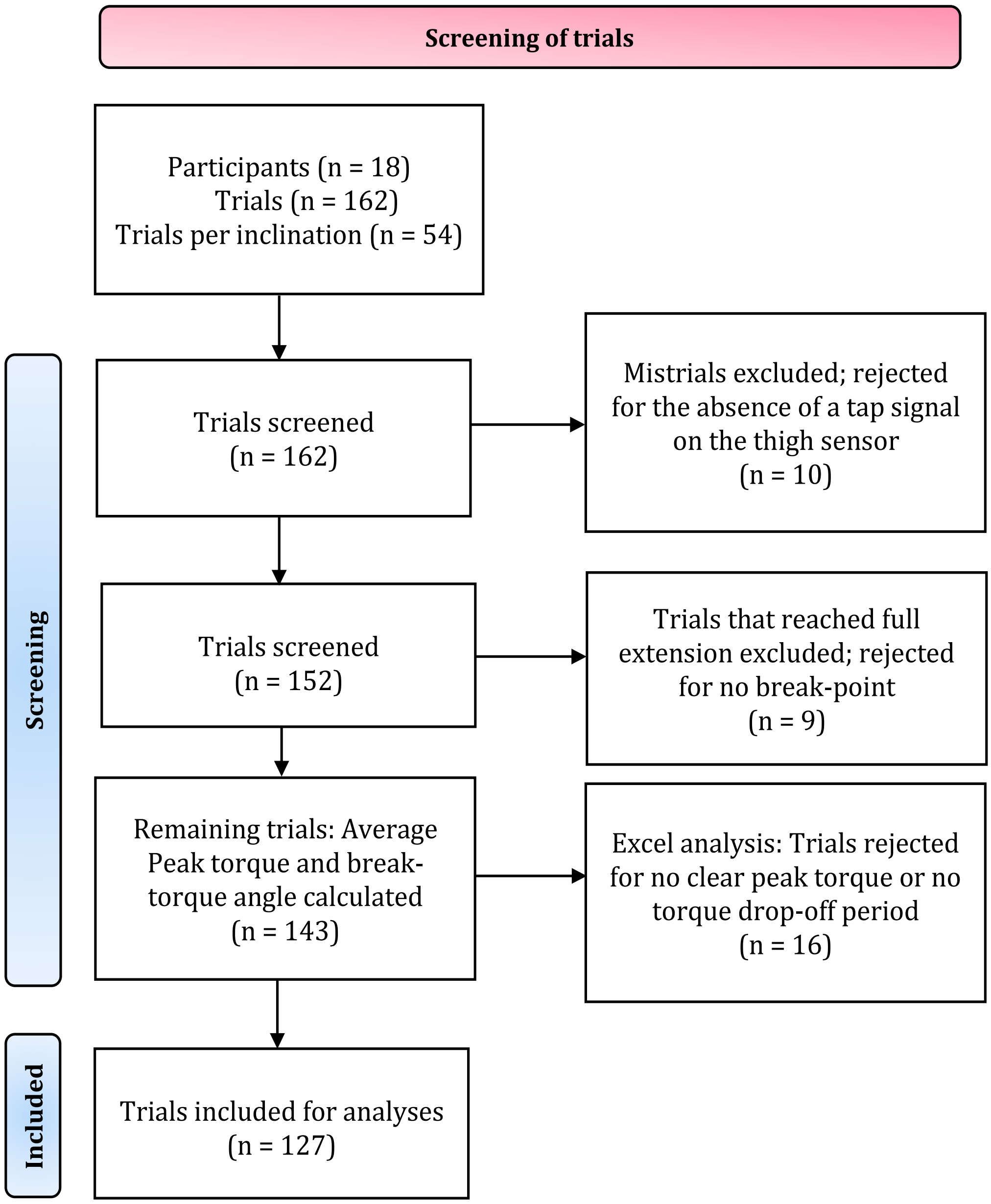


Figure 21: A modified PRISMA flow diagram for trial inclusion (Moher et al., 2009).

4.3.5 Statistical analyses

The angle reached at BTA was calculated from the accumulated increase in knee joint angle during the descent towards full knee extension (180°). The resulting data were statistically processed in GraphPad Prism 8.43 (GraphPad Software Inc). Descriptive statistics for all the remaining 127 trials were calculated and reported as mean ± standard deviation **(Table 7)**. In addition to reporting mean ± SD, the CV% was calculated for each metric at each inclination; CV%=(SD ±

Mean) x 100. CV% provides a measured of variability relative to the mean, allowing comparison of variability across metrics with different units. The minimum and maximum values were also reported to describe the fill range of participant responses (**Table 7)**. The D'Agostino-Pearson test was used for testing of normality rather than the Shapiro-Wilk test used in the previous study. The D'Agostino-Pearson test evaluates both skewness and kurtosis, providing a comprehensive assessment of deviation from a normal distribution. This choice was suitable given the moderate sample size and the presence of multiple outcome variables across the different inclinations. The results indicated that all outcome measures were normally distributed ($p>0.05$), satisfying the assumption of normality require for parametric testing. One-way repeated measures ANOVA were performed to identify differences between eccentric knee flexor torque (Nm), angular velocity of the knee joint ($deg \cdot s^{-1}$) and relative trunk-to-thigh angle (°), at break torque angle (°) in different inclinations. Where significant effects were detected, post hoc t tests with Tukey's HSD were applied to determine where any mean differences occurred. The level of statistical significance was set at $p<0.05$ for all analyses. Mean differences of all measurements were reported with their 95% confidence intervals. Effect sizes were calculated by Hedges' g and interpreted as small ($g \geq 0.2$), moderate ($g \geq 0.5$) and large ($g \geq 0.8$) (J. Cohen, 2013). In addition, omega squared (ω^2) effect sizes were computed for all ANOVAs to estimate the proportion of variance explained by inclination, with values of 0.01, 0.06, and 0.14 representing small, medium, and large effects, respectively (Lakens, 2013).

4.4 Results

Descriptive statistics for each metric are shown in **Table 7** and reported as mean ± standard deviation. The variability for each metric is reported as the coefficient of variation (CV%), and the minimum to maximum value range. Performance and injury-risk metrics (peak torque and BTA) are shown in **Figure 22** illustrating their significance across inclinations. NHE technique metrics (AVK at peak-torque, and RTA at peak-torque) are shown in **Figure 23** illustrating their significance across inclinations.

4.4.1 Peak-torque and break-torque angle

Altering inclination did not affect eccentric knee flexor peak torque, $F(2,34)=0.952$, $p=0.389$, $\omega^2<0.01$. Peak torques at altered inclinations can be seen in **Table 7** and **Figure 22**. Mean ± SD peak torque values were 132.0 ± 63.1Nm (CV=47.8%, range: 20.1-246.1) at DEC, 149.7 ± 70.1Nm (CV=46.8%; range: 50.5-316.7) at FLAT, and 148.9 ± 64.9Nm (CV=43.6%; range: 72.3-275.4) at INC. Changes in mean BTAs at altered inclinations can be seen in **Table 7** and **Figure 22**. Changing inclination significantly affected the BTA, $F(2,34)=63.85$, $p<0.01$, $\omega^2=0.78$, which increased when the NHE was performed at INC (134.1 ± 8.6°, CV=6.4%) compared to both the DEC (112.1 ± 8.3, CV=7.4%) ($p<0.01$, $g=2.599$) and conventional FLAT NHE (126.0 ± 9.8°, CV=7.8%) ($p<0.01$, $g=0.885$) (**Figure 22**).

Table 7: Mean, standard deviation, coefficient of variation, and range (minimum-maximum) for each variable considered in the study. The effect of different inclinations on eccentric knee flexor torque and break-torque angle shown.

Variables	Mean ± SD	CV (%)	Range (Min-Max)
Torque (Nm)			
Decline	132.0 ± 63.1	47.8	20.1 - 246.1
Flat	149.7 ± 70.1	46.8	50.5 - 316.7
Incline	148.9 ± 64.9	43.6	72.3 - 275.4
Break-torque angle (°)			
Decline	112.1 ± 8.3 *a c*	7.4	98.5 - 131.7
Flat	126.0 ± 9.8 *a b*	7.8	108.8 - 149.4
Incline	134.1 ± 8.6 *b c*	6.4	118.8 - 151.6
Angular velocity of the knee joint at peak torque (deg·s^{-1})			
Decline	23.8 ± 14.4	60.5	7.3 - 68.2
Flat	29.2 ± 22.6	77.4	3.6 - 93.4
Incline	24.5 ± 22.6	92.2	4.5 - 96.3
Relative thigh-to-trunk angle at peak torque (°)			
Decline	20.4 ± 10.4	51.0	1.8 - 53.8
Flat	16.7 ± 10.8	64.7	0.4 - 44.7
Incline	20.2 ± 11.2	55.4	3.1 - 51.1

a denotes significant difference between Decline vs. Flat ($p<0.01$), *b* denotes significant difference between Flat vs. Incline ($p<0.01$), *c* denotes significant difference between Decline vs. Incline ($p<0.01$).

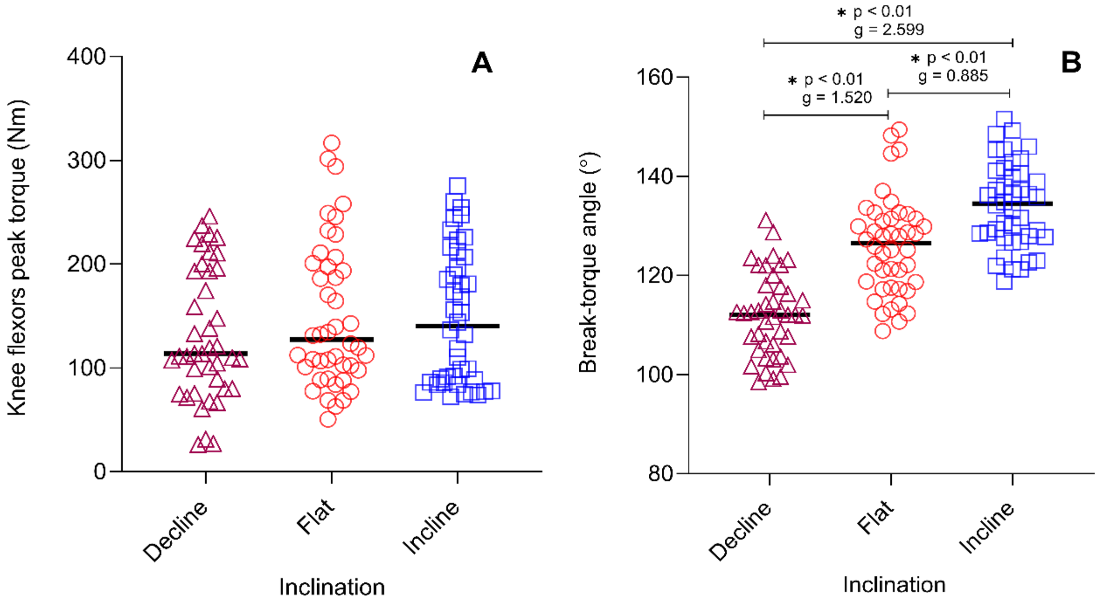


Figure 22: Eccentric knee flexor peak torque (A) and break-torque angle (B) at each inclination (decline n=41, flat n=44 and incline n=42) whilst performing the Nordic hamstring exercise on the HALHAM°. Asterisks (*) indicate any significant differences between inclination.

4.4.2 Angular velocity of the knee joint, and relative trunk-to-thigh angle at break-torque

Altering inclination had no significant effect on AVK, $F(2,34)=0.88$, $p=0.42$, $\omega^2<0.01$, however large variability was reported for AVK at BTA in all inclinations. Mean ± SD AVK values were 23.8 ± 14.4 deg·s^{-1} (CV=60.5%; range: 7.3-68.2) at DEC, 29.2 ± 22.6 deg·s^{-1} (CV=77.4%; range: 3.6-93.4) at FLAT, and 24.5 ± 22.6 deg·s^{-1} (CV=92.2%; range: 4.5-96.3) at INC, with FLAT reporting the highest mean difference. Similarly, altering inclination had no significant effect on RTA, $F(2,34)=1.60$, $p=0.21$, $\omega=0.03$) however large variability can be seen across all inclinations. Mean ± SD RTA values were 20.4 ± 10.4° (CV=51.0%; range: 1.8-53.8) at DEC, 16.7 ± 10.8° (CV=64.7%; range: 0.4-44.7) at FLAT, and 20.2 ± 11.2° (CV=55.4%; range: 3.1-51.1) at INC, with DEC reporting the highest mean difference and range between trials (20.4 ± 10.4°; 1.8-53.8°) (**Table 7**). AVK and the RTA at different inclinations can be seen in **Figure 23**.

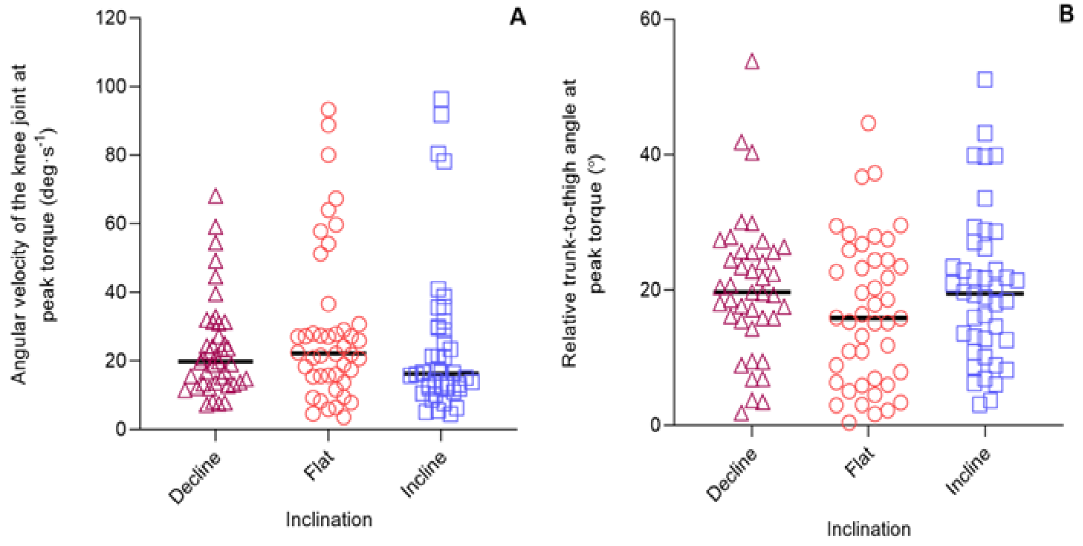


Figure 23: Angular velocity of the knee joint (A) and relative trunk-to-thigh angle (B), at peak torque across the inclinations.

4.5 Discussion

The aim of the study was to use the HA*L*HAM° device to manipulate the torque-length relationship of the knee flexors to reach longer muscle lengths, whilst still being able to reach supramaximal torques. The findings demonstrate the hypothesized rightward shift of (*proxy)* muscle length. NHE BTA significantly increased when performed at INC compared to both the DEC and standard NHE (**Table 7**) however, there was no significant change in peak torque across the 3 inclinations. This suggests that an incline NHE may be able to train the knee flexor muscles at more extended lengths, similar to those seen in sprinting where the site of most HSIs occur. This rationale has been strengthened by recent research conducted by Šarabon et al., (2019), where a custom device was used to alter the slope of the starting knee angle when performing a NHE. They reported that modified variations of the NHE (20° and 40° slopes) allowed participants to reach peak knee and hip torques at longer estimated hamstring lengths (20˚slope = 75.0 ± 7.3˚; 40˚slope = 87.9 ± 7.5˚) compared to the conventional flat NHE (56.1 ± 9.1˚). Using the HA*L*HAM° incline slope for eccentric long-length muscle training may favourably affect architectural adaptations within the knee flexor muscles, such as increased fascicle length and muscle hypertrophy (Maeo et al., 2021; Tyler et al., 2017). However, further studies are needed to confirm the occurrence of these adaptations and if they are greater when compared to using the conventional (FLAT) NHE. Relative specific strength, where an individual may possess a comparatively greater eccentric strength at a particular slope angle, should also be considered in terms of its relationship to NHE performance and HSI prevention (Marušič et al., 2020; Šarabon et al., 2019). Employing the decline slope specifically targeted shorter muscles lengths with the lowest angular velocity, making it a good approach for introducing the NHE to beginners or for rehabilitating players recovering from injury (Keerasomboon et al., 2022; Soga et al., 2021). These findings show that the decline slope produces torque production at shorter muscle lengths whilst producing less acceleration, making it suitable for athletes who require a controlled stimulus. Therefore, the HA*L*HAM° may offer value for both progression and regression options, as different inclinations can adjust the torque-length relationships and angular velocity to suit the stage of return-to-play protocols or performance enhancement goals.

It is well recognized that a multifactorial approach should be considered in HSI prevention (Mendiguchia et al., 2017; Naclerio et al., 2015; Valle et al., 2015; Van Dyk et al., 2017). Any device focused on specific individual risk factors should therefore only be considered as an additional tool to inform injury data (associations rather than prediction) and return-to-play outcomes (Amundsen et al., 2023; Green et al., 2018; Van Dyk et al., 2017). It should be acknowledged that the reliability of several angular-torque metrics in the study was compromised by substantial inter-individual variability in exercise quality. Despite instructing participants to remain fully extended at the hip whilst executing a slow, controlled descent until supramaximal failure, enforcing and controlling this consistently across trials was challenging. This variability was reflected in the high CV values and wide ranges observed for AVK (up to 92%) and RTA (up to 65%) at BTA across inclinations (**Table 7**). Such large between and within-participant variability suggests that current HALHAM° protocols do not sufficiently constrain technique, limiting the reliability of secondary outcome measures (exercise quality). However, altering the inclination had no significant effect on AVK or the RTA

(**Table 7** and **Figure 23)** and it can therefore be assume that differing inter-individual technique rather than inclination was the cause of these effects.

Primary metrics such as peak torque and BTA should remain the focus for evaluating performance, while secondary metrics such as AVK and RTA should be interpreted with caution. Although these technique-related metrics may lack sufficient reliability for longitudinal tracking, they offer valuable contextual information about acute NHE execution. The low reliability of AVK and RTA is unsurprising, as NHE movement patterns naturally vary and technique is inherently inconsistent across participants. To overcome limitations related to inter-individual variability, future modifications to the HALHAM° device should prioritise greater control of hip position and descent control, for example through the integration of an inertial measurement unit (IMU) and biofeedback programme. An IMU, which combines accelerometers, gyroscopes, and magnetometers to measure angular orientation and velocity, could assist real-time feedback, enhance portability, and allow constriction form ferrous materials without comprising data quality (Ayman et al., 2020; Huang et al., 2023). Such as system should improve measurement reliability and enable a clearer assessment of how NHE technique specifically influences angular-torque mechanics.

4.6 Conclusion

The HA*L*HAM° allows modification and measurement of the torque-angle relationship of the knee flexors and can target the hamstrings at longer lengths using an incline slope mechanism. Given the high variability in exercise execution future directives should implement an IMU-based approach and integrate a feedback system to better control hip position and knee extension speed, allowing a more precise assessment of how technique influences angular-torque metrics.

4.7 Chapter conclusion statement

i. The use of the BTA metric is supported by the low within-session variability observed in this study (<10%). This shows that BTA can be reliably measured regardless of inclination, making it a practical metric for practitioners to assess changes in muscle length and compare performance both within and between participants.

ii. Inclination of the NHE leads to hamstring muscle failure at longer muscle lengths without reductions in the maximal force applied by the muscle. Therefore, the NHE performed on an incline may be a more effective training intervention, specific to the proposed mechanism of HSI during sprinting that occurs whilst the muscle is rapidly lengthening.

iii. Due to a large inter-individual variability in technique in this study, future modifications to the HALHAM° pilot device should look to better control hip position and knee extension speed, and thus further explore the influence of technique on angular-torque metrics.

iv. Other modifications will look to strengthen the devices viability and usability. New alterations should undergo stringent validity and reliability protocols to ensure the devices integrity and the accuracy of any future data collection.

Chapter 5

Pilot study - Validation of an IMU-Based HA*L*HAM° System for Nordic Hamstring Exercise Assessment.

(*Sub-chapter*: Hardware Modifications and Considerations for Biofeedback Integration into the HA*L*HAM° System).

This chapter examines the validity and reliability of the prototype hamstring testing device, HA*L*HAM°, with an integrated IMU system. Building on the proposed IMU-based modification introduced in **Chapter 4,** the study assesses whether the IMU maintains measurement accuracy and reliability compared to the previously used Polhemus motion tracking system. While the Polhemus system remains the gold standard for electromagnetic motion tracking, its susceptibility to ferromagnetic interference, limited portability, and high cost make it less suitable for repeated field or clinical testing. Furthermore, the sub-chapter discusses hardware and software modifications aimed at improving the HA*L*HAM° device's practical efficacy as a hamstring assessment tool and explores preliminary considerations for integrating a biofeedback system.

5.1 Chapter aim

The aim of this chapter was to determine the validity and reliability of an IMU-based HA*L*HAM° system compared against the established Polhemus gold standard system, with the purpose of improving portability, robustness, and commercial viability.

5.1.1 Study objectives

i. Assess whether integrating an IMU-based system into the HA*L*HAM° device maintains measurement accuracy (validity) when compared to the Polhemus system.

ii. Assess the consistency and repeatability (reliability) of IMU measurements across trials within individuals.

iii. Explore hardware modifications and software considerations for integrating a biofeedback system into the HA*L*HAM° device, to inform future NHE exercise quality control.

5.1.2 Hypothesis

i. The IMU-based HA*L*HAM° system will demonstrate acceptable validity and reliability compared to the Polhemus gold standard system.

ii. Integration of a biofeedback system is expected to reduce variability in technique and improve measurement reproducibility in future studies.

5.2 Introduction

Specifically engineered for concurrent measurement of joint angle and torque during the NHE, the efficacy of the HA*L*HAM° centres on its ability to provide accurate and consistent measurements. Therefore, evaluating validity and reliability is central to ascertaining the value of such a device. Validity refers to the extent to which an instrument accurately measures what it is intended to measure (Blumberg et al., 2005; Robson, 2011). Reliability refers to the reproducibility of the values of these measurements in repeated trials on the same individuals (Hopkins, 2000). Stringent validity and reliability protocols establish good research and decrease the opportunity for researcher bias (Singh, 2014), enhancing the accuracy of academic work and addressing any effects of measurement errors (Tavakol & Dennick, 2011). In development, the HA*L*HAM° prototype used a laboratory grade 3-dimensional motion tracking system (Liberty®) developed by Polhemus (Colchester, Vermont, USA) to ascertain the angular data driven metrics by quantifying angular displacement. Polhemus is widely regarded as the gold standard measure in electromagnetic motion tracking due to its high accuracy, with position and orientation measurements within ± 0.2°, and a high sampling rate of 240Hz (Cescon et al., 2015), ensuring real-time motion measurement with minimal latency. Comparative studies have demonstrated its superior accuracy and reliability over other tracking technologies (Lloréns et al., 2015).

However, its application has challenges when dealing with ferromagnetic materials as these materials can introduce interference and inaccuracies into the tracking data, resulting in misalignment or erroneous readings of the tracked object's position and orientation (Nixon et al., 1998; Poulin & Amiot, 2002). One issue can be signal distortion in the magnetic field measurements, which compromises the accuracy and reliability of the motion tracking system. Additionally, limited tracking range and data drift can occur. The magnetic field may not propagate as intended, limiting the system's ability to capture motion date accurately over a certain distance (Yaniv et al., 2009). For example, if steel is present in the floor, this could be a particularly relevant issue in the NHE as an individual approaches the end position of the movement, closest to the floor. Furthermore, ferromagnetic materials contribute to data drift, where the tracked object's position and orientation gradually deviate from the correct values over time and become more pronounced (Nixon et al., 1998). This could significantly impact the reliability of conducting multiple NHE trials.

To overcome these limitations an IMU was proposed as an alternative measurement method. An IMU is a sensor device that typically combines multiple accelerometers, gyroscopes and magnetometers to measure the orientation of a rigid body that they are attached to, and report on angular rate (Huang et al., 2023). Integrating an IMU with the HA*L*HAM° would make it more portable and lower cost (Ayman et al., 2020). Furthermore, being able to build it from ferrous material would make it more versatile, commercially viable and robust. Assessing against the gold standard Polhemus will validate the device's integrity and enhance the reliability of any future collected data.

5.3 Methods

Pilot work was conducted to assess the level of agreement between the Polhemus system and the integrated IMU system of the HA*L*HAM° to determine angular metrics. The Polhemus thigh sensor and IMU were positioned on a custom-made plastic carrier with angled ends to help align both sensors laterally on the upper leg at equal distance away from the greater trochanter and lateral femoral epicondyle (**Figure 24**). The trunk sensor was also positioned laterally at an equal distance from the greater trochanter to the shoulder bursa.

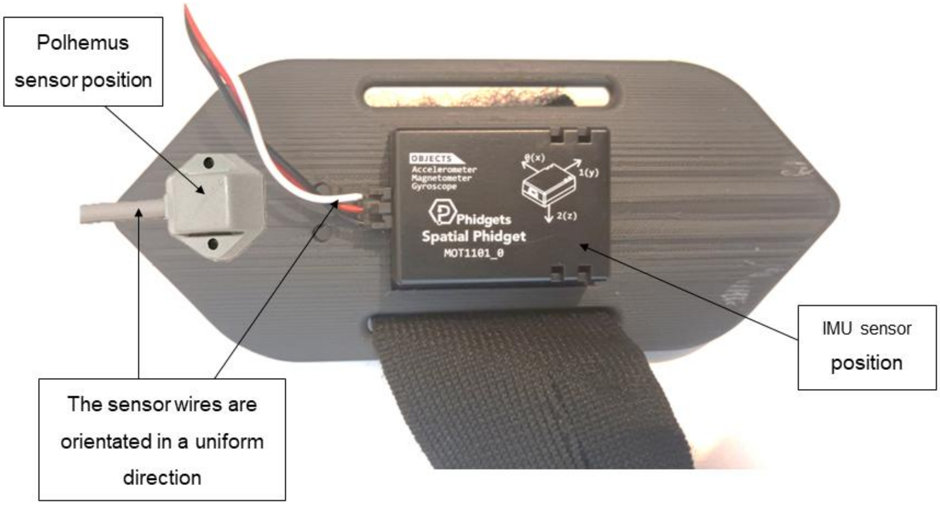


Figure 24: CAD of holder for both Polhemus sensor and IMU.

5.3.3 Participants

Five participants (n=4 male, 1 female) were recruited to participate in this pilot study (mean ± SD age 40 ± 12years, height 173.7 ± 14.8cm, and body mass 74.6 ± 14.7kg). Only 5 participants were recruited to compare IMU and Polhemus metrics, as the primary aim was to assess measurement agreement and consistency between the two systems in calculating the same angular data, rather than to examine inter-subject variability across a large population. A heterogeneous sample was deliberately chosen, including a diverse representation of gender, age, ability, height and body mass. While such diversity does not increase the internal validity of the measurements, it does strengthen the *ecological* validity and external applicability of the findings (Andrade, 2018). Specifically, testing across a range of participant characteristics allows for a more realistic assessment of how robust each system is under differing conditions that are likely to occur in practice (Andrade, 2018; Giraudeau et al., 2022). For example, variations in body mass and limb dimensions may influence sensor placement or signal quality and ensuring that the prototype is exposed to such variation makes the evaluation more reflective of real-world settings (Huang et al., 2023). Given that the NHE is performed by a wide variety of individuals, from professional athletes to recreational exercisers, this diversity makes the research more practical and relevant, with findings that are applicable across different populations.

5.3.4 Procedures

Each participant completed 5 bilateral NHE reps on the HA*L*HAM° (n=25 trials) following a standardised sub-maximal warm-up of 3 repetitions to synchronise the Polhemus and IMU data. Participants were instructed to tap the thigh sensor holder at the beginning of each NHE rep and asked to gradually lean forward at the slowest possible speed whilst maintaining a neutral trunk alignment with the hips fixed in line with the knee and shoulder joints (Mjølsnes et al., 2004). Participants performed the action until they could no longer withstand the torque around their knee flexors, using their hands to buffer the fall onto a platform (Petersen et al., 2011; Sconce et al., 2015). A rest period of ≥6 secs between trials was sufficient for participants to fully recover for the next repetition (Alt et al., 2022). The Polhemus Liberty® software was used to collect kinematic data from the two sensors sampled at 240Hz. Raw IMU data were exported in .CSV format and processed on a personal computer via a Phidget Bridge data acquisition board (Phidgets Inc., Calgary, Canada). The IMU data were processed using a custom coded script in MATLAB software (version R2022b, MathWorks, Inc., Natick, MA) and returned sagittal angles occurring in the anterior-posterior plane. The following variables were subsequently calculated using a researcher custom template:

- **Relative thigh break-angle (RThighBA)** ~ representing the definitive peak torque value and its corresponding thigh angle. The resultant angle being the relative difference between start and break-point.
- **Relative trunk break-angle (RTrunkBA)** ~ representing the definitive peak torque value and its corresponding trunk angle. The resultant angle being the relative difference between start and break-point.

- **Relative trunk-to-thigh angle (RTA)** ~ representing the angle between the thigh and the trunk throughout the NHE ROM, relative to a fixed axis. Subsequently, RTA at break-point was extracted from the data.

The calculated variables (RThighBA, RTrunkBA, and RTA) were derived solely for the purpose of comparing outputs between the Polhemus Liberty® motion tracking system and the IMU sensors. As these present geometric transformations of angular data obtained from a validated 3D tracking system, their reliability depends on the accuracy of the underlying hardware rather than repeated human performance. The Polhemus Liberty® system has been shown to provide highly reliable and precise motion capture data, with sub-millimetre positional accuracy and low angular drift across repeated trials (Cescon et al., 2015; Wheare et al., 2021). Therefore, these derived variables were considered valid measures of assessing agreement between systems rather than independent performance outcomes requiring separate reliability testing.

5.3.5 Statistical analyses

Descriptive statistics are expressed as mean ± SD. Normality of the difference scores between Polhemus and IMU data was confirmed using the Shapiro-Wilk test, supporting the use of parametric tests. Despite the small sample size (n=5), paired t-tests were deemed appropriate because they are robust for within-subject comparisons when normality is satisfied (De Winter, 2013). Agreement between the two measurement systems was further examined using Bland-Altman analysis (Bland & Altman, 1986), a method recommended for assessing the validity of new measurement techniques against established reference systems (Giavarina, 2015). The assumptions for the Bland-Altman analysis (normally distributed differences and homoscedasticity) were verified using Shaprio-Wilk tests and by visually inspecting Bland-Altman plots for any evidence of systematic bias of unequal variance across the measurement range. Limits of agreement were calculated as the mean bias ± 1.96 x SD, representing the 95% confidence interval of the differences (Balsalobre-Fernández et al., 2015). The data was subsequently statistically processed in GraphPad Prism 8.43

(GraphPad Software Inc). Significance level was defined as $p<0.05$. Effect sizes were calculated using Hedges' g, which includes a correction for small-sample bias, and interpreted as small ($g \geq 0.2$), moderate ($g \geq 0.5$) and large ($g \geq 0.8$) (J. Cohen, 2013). Validity of the IMUs was examined using the Pearson correlation test for consistency with Polhemus. The magnitude of the correlation was established based on the following criteria: $r=1$, perfect positive correlation; $0.7 \leq r<1$, strong positive correlation; $0.3 \leq r<0.7$ moderate positive correlation; $0 \leq r<0.3$, weak positive correlation; $r=0$, no correlation.

5.4 Results

Figure 25 shows the correlation of RThighBA between Polhemus and an IMU. The Pearson correlation between the two measurement systems was strongly correlated ($r^2=0.9889$, $p<0.0001$) indicating a positive linear relationship. **Figure 26** shows the agreement of RThighBA between Polhemus and an IMU. The RThighBA values obtained were 111.2 ± 3.36° and 111.3 ± 3.10° (where full extension = 180°) for the Polhemus and IMU respectively, indicating no significant difference between the datasets ($d=0.031$, $p=0.1016$). The mean difference between the Polhemus and IMU was -0.15 ± 0.43°. with the limits of agreement ranging from -0.99° to 0.70° (**Table 8** and **Figure 26**).

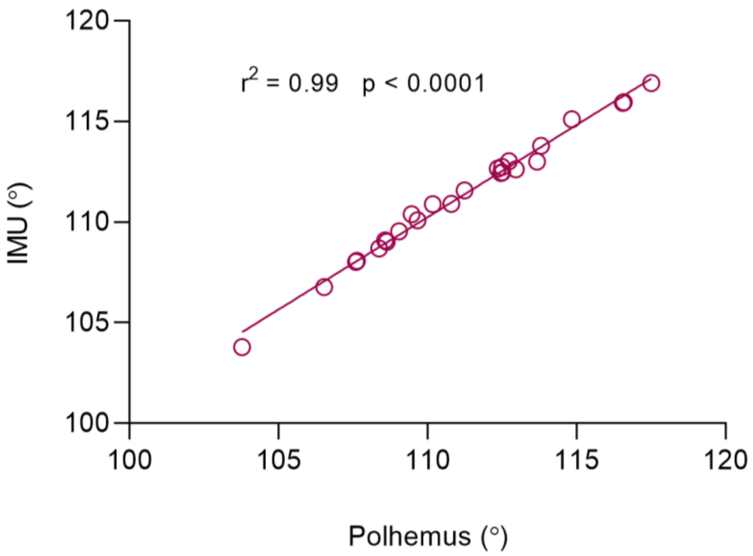


Figure 25: The correlation between the relative thigh break-angle metric obtained using the Polhemus system and the corresponding metric determined via an inertial measurement unit.

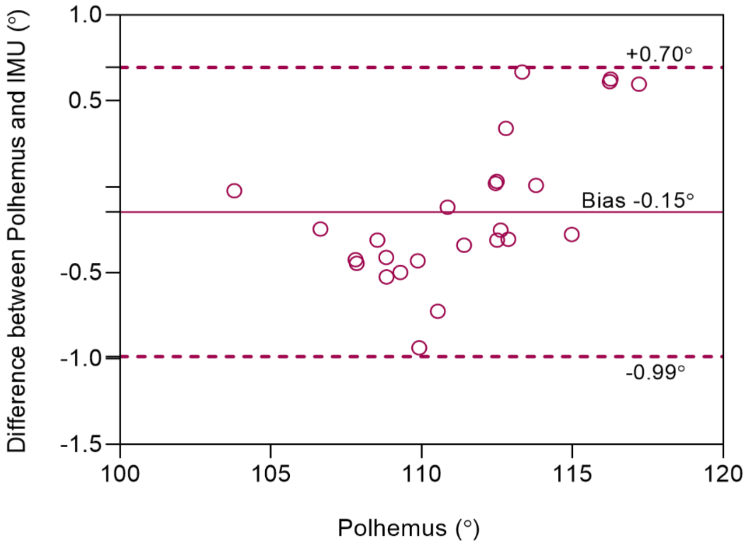


Figure 26: Bland-Altman plot: Average versus difference between measurements of the relative thigh break-angle metric (Polhemus subtracted by the inertial measurement unit). Displays the limits of agreement for the two methods (mean difference plus or minus 1.96 standard deviation).

Figure 27 shows the correlation of RTrunkBA between Polhemus and an IMU. The Pearson correlation between the two measurement systems was strongly correlated (r^2=0.9927, $p<0.0001$) indicating a positive linear relationship. **Figure 28** shows the agreement of RTrunkBA between Polhemus and the IMU. The RTrunkBA values obtained were 33.46 ± 6.16° and 33.62 ± 6.23° (where full hip extension=90°) for the Polhemus and IMU respectively, indicating no significant difference between the datasets (d=0.026, p=0.1535). The mean difference between the Polhemus and IMU was -0.16 ± 0.53°. with the limits of agreement ranging from -1.20 ° to 0.89° (**Table 8** and **Figure 28**).

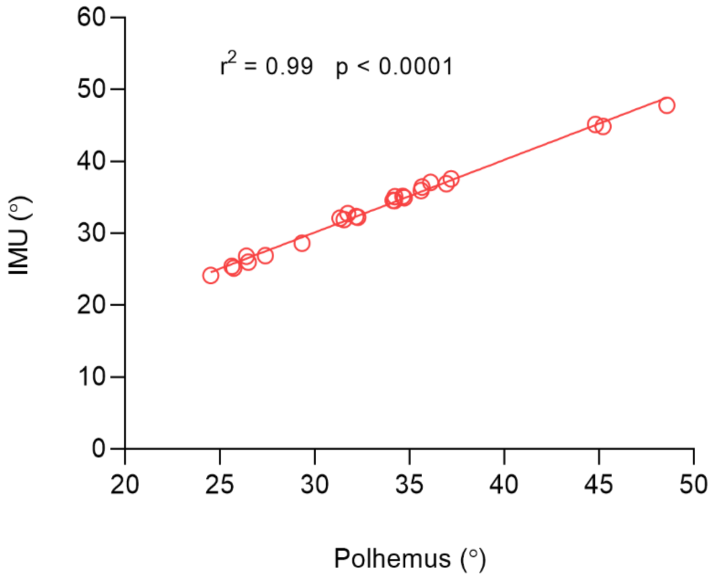


Figure 27: The correlation between the relative trunk break-angle metric obtained using the Polhemus system and the corresponding metric determined via an inertial measurement unit.

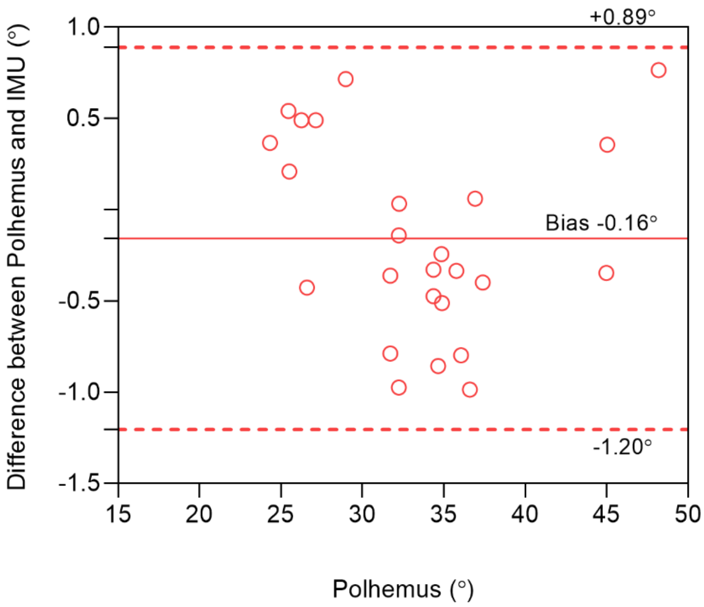


Figure 28: Bland-Altman plot: Average versus difference between measurements of the relative trunk break-angle metric (Polhemus subtracted by the inertial measurement unit) for. Displays the limits of agreement for the two methods (mean difference plus or minus 1.96 standard deviation).

Figure 29 shows the correlation of RTA at break-point between Polhemus and the IMU. The Pearson correlation between the two measurement systems was strongly correlated (r^2=0.9949, p<0.0001) indicating a positive linear relationship. **Figure 30** shows the agreement of RTA at break-point between Polhemus and the IMU. The RTA at break-point values obtained were 12.26 ± 6.66° and 12.28 ± 6.63° for the Polhemus and IMU respectively, indicating no significant difference between the datasets (d=0.003, p=0.9068). The mean difference between the Polhemus and IMU was -0.01 ± 0.48°. with the limits of agreement ranging from -0.95° to 0.93° (**Table 8** and **Figure 30**).

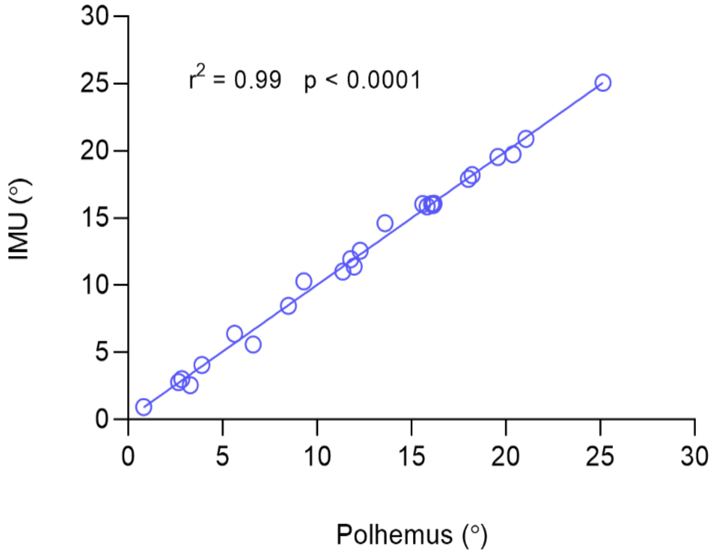


Figure 29: The correlation between the relative trunk-to-thigh angle at break-point metric obtained using the Polhemus system and the corresponding metric determined via an inertial measurement unit.

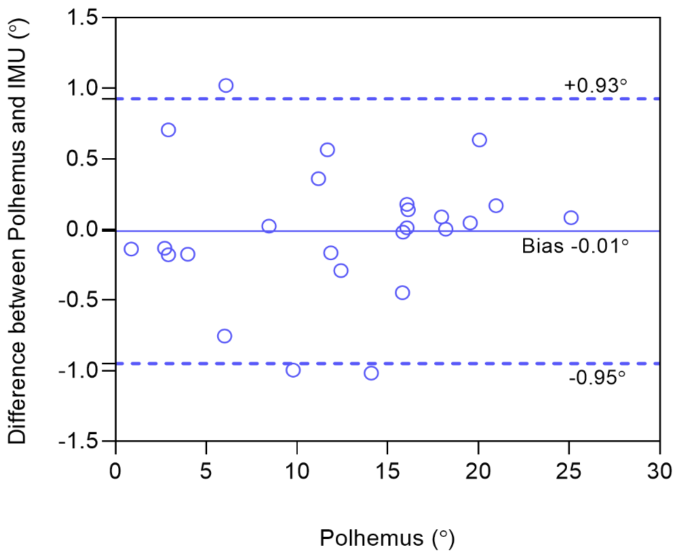


Figure 30: Bland-Altman plot: Average versus difference between measurements of the relative trunk-to-thigh angle at break-point metric (Polhemus subtracted by the inertial measurement unit). Displays the limits of agreement for the two methods (mean difference plus or minus 1.96 standard deviation).

Table 8: Table showing the absolute limits of agreement for angular metrics assessed using the Polhemus system and the inertial measurement unit system.

	Lower 95% Agreement (°)	Mean diff *'Bias'* (°)	SD of bias (°)	Upper 95% Agreement (°)
Relative thigh break-angle	-0.99	-0.15	0.43	0.70
Relative trunk break-angle	-1.20	-0.16	0.53	0.89
Relative trunk-to-thigh angle	-0.95	-0.01	0.48	0.93

Table 9: Table showing the resulting mean of the standard deviations (n=15, n=44 trials) from previously published HALHAM° inter-individual intra-session data (Sconce et al., 2021a).

	Means of SD (°)
Break point-angle	2.81
Break-torque angle	2.85
Relative trunk-to-thigh angle at break-torque angle	4.77

5.5 Discussion

The IMU-based HA*L*HAM° system demonstrated excellent validity and reliability when compared to the gold-standard Polhemus motion capture system. Validity was confirmed by very strong correlations (near perfect) observed for RThighBA, RTrunkBA and RTA at break-point when measured by the Polhemus and then determined through IMUs respectively (**Figure 25** and **Figure 27** and **Figure 29**). Bland-Altman analysis indicated minimal systematic bias and narrow limits of agreement across all metrics, confirming that the IMU system accurately reflects angular kinematics captured by the gold-standard system. Reliability was supported by low trial-to trial variability within participants, with standard deviations consistent with previously published HA*L*HAM° data (Sconce et al., 2021a).

Comparatively, Soga, Yamaguchi, et al., (2023) examined a similar methodology using a smartphone application (Nordic Angle) against motion analysis software (Frame-DIAS, DKH Inc., Tokyo, Japan) with seven male participants. Their sample size was calculated a priori using G*power (ρ H1=0.9, α=0.05, power=0.8), resulting in n=5 as the minimum required. They reported a Pearson correlation of r=0.92, p<0.0001 between the two methods, however, a small yet significant systematic difference was observed (d=0.27, p=0.029), suggesting less agreement than found in the present study. In contrast, the IMU system integrated with the HA*L*HAM° showed no significant differences compared to Polhemus measurements, indicating lower bias and random error. The mean difference for RThighBA (the metric most closely related to the break-point angle) was -0.15 ± 0.43°, with limits of agreement ranging from -0.99° to 0.70°, substantially lower than the 3.0 ± 4.3° (limits -5.5° to 11.4°) reported by Soga, Yamaguchi, et al., (2023). Post-hoc calculations for the present study (n=5) indicate moderate power (~61%) for detecting the observed correlations, which is typical for pilot validity studies (Sorzano et al., 2017). Despite the small sample size, the very high correlations and narrow limits of agreement show that the IMU system provides highly consistent and reliable angular kinematic data.

The relatively wide SD observed across some participants primarily reflects inter-individual variability in the deliberately heterogenous sample rather than measurement error. The IMU system reliably captures intra-session angular metrics despite heterogeneity in the sample. **Table 8** and **Table 9** provide quantitative evidence that the IMU-based HA*L*HAM° system captures angular kinematics with accuracy and reliability comparable to the Polhemus system. Minimal bias, narrow limits of agreement, and consistency with published variability metrics collectively confirm that IMU integration achieves the chapter aim of providing a valid and reliable method of assessing angular performance metrics during the NHE, offering greater portability and practicality for both research and field-based applications.

5.6 Conclusion

Given the low bias, high correlation with the gold-standard system, and consistent trial-to-trial reliability, it is recommended that future HA*L*HAM° data collection relies solely on the integrated IMU system. This approach improves portability and practical applicability without compromising measurement accuracy, making it well suited for both laboratory and field-based NHE assessment.

(*Sub-chapter*: Hardware Modifications and Considerations for Biofeedback Integration into the HA*L*HAM° System).

5.7 Practical evaluation of the HALHAM°

While the analyses presented above establish the validity and reliability of the HALHAM° in comparison to a gold-standard measurement system, it is equally important to assess the device in terms of its practical application for NHE testing. Beyond technical accuracy, a hamstring testing device must also demonstrate usability, safety and alignment with established assessment criteria if it is to be adopted in both research and applied practice. The following sub-chapter provides a practical evaluation of the HALHAM° prototype against the **A**ssessing **N**ordic **H**amstring **E**xercise **Q**uality (ANHEQ) rating scales for both NHE assessment and NHE intervention studies (Alt et al., 2022; Alt & Schmidt, 2021a) (**Figure 31**). The ANHEQ rating scales were specifically developed to provide a standardised and domain-specific framework for assessing the quality of NHE performance and intervention reporting, addressing the limitations of generic quality tools such as the PEDro and TESTEX scales (Alt & Schmidt, 2021a) . In their development study, 18 expert raters, including sport scientists, physiotherapists, and elite coaches, evaluated published NHE studies using two eight-item scales (maximum score 13). The results demonstrated excellent inter-rater agreement (87 ± 5% for assessments; 88 ± 6% for interventions) and high inter-rater reliability, with total ANHEQ score coefficients of 0.829 for assessments and 0.772 for interventions, confirming the reliability and validity of the scales for evaluating NHE execution quality and data presentation.

Further evidence of construct validity and practical applicability was provided in a subsequent scoping review of 71 NHE assessments and 83 interventions (Alt et al., 2022). That review used the ANHEQ scales to evaluate study quality across the literature and identified systematic deficits in reporting and execution parameters such as rigid fixation, kneeling height and familiarisation procedures. The review highlighted that the scales effectively discriminated between high- and low-quality studies and supported the development of evidence-based guidelines for future NHE research design and reporting. Therefore, the ANHEQ rating scales can be regarding as reliable and valid tools for the structured evaluation of NHE technique and implementation, justifying their use in the present study to assess the HA*L*HAM° prototype. The final part of this chapter details the modifications subsequently implemented to optimise the HA*L*HAM° design. These include hardware adjustments, and the integration of a biofeedback system ensuring that the device is not only scientifically robust but also practical and responsive to real-world training and testing environments.

5.8 Assessing Nordic hamstring exercise quality

To assess the quality of the current design of the HA*L*HAM° for NHE assessment a self-evaluation was conducted using the ANHEQ rating scale, and a score of 9 from a maximum of 13 points was reported (**Table 10**). The only significant item missing from the device or protocol, was feedback for individuals regarding their target movement speed during the NHE. Velocity was reported subsequently as an AVK metric and verbally participants were encouraged to control their descent speed, but constant target movement speed was not available as a tool for to participants to guide their exercise technique in real-time. To ensure the quality of NHE testing a constant target movement speed should be incorporated to fulfil the requirement of the ANHEQ rating scale for NHE testing. This is important to achieve reliable results as an alteration of movement speed before break-point will impact torque production due to altered hamstrings muscle-tendon unit stiffness (Alt & Schmidt, 2021a; Bohm et al., 2015; Mjølsnes et al., 2004; Wiesinger et al., 2020). For desired muscle adaptation a single repetition should last 4 - 6s with importance linked to time under tension at knee flexion angles of 135 - 180° (where full extension = 180°) (Bohm et al., 2015).

Item	ANHEQ rating scales and explanation	Reference value A1	A2	A3	A4
(1) Rigid fixation	*2 points*: fixed/rigid resistance at the heels *0 points*: partner assistance or not reported	0	2	2	2
(2) Knee position	*2 points*: feasible patellar glide (tuberositas tibiae placed on an edge, knees do not touch the floor) *1 point*: limited or partially feasible patellar glide (e.g., appropriately cushioned surface) *0 points*: patellar glide not feasible or not identifiable	0	0	1	1
(3) Kneeling height	*1 point*: shanks are placed at least 15 cm above the floor to enable full knee extension *0 points*: no/insufficient elevation or not identifiable	0	1	0	0
(4) Separate familiarization	*1 point*: a separate familiarization session was conducted to teach proper NHE technique *0 points*: instructions/'familiarization' at testing day or not reported	0	1	0	1
(5) Diagnostic tools	*2 points*: results of ≥ 2 diagnostic tools (kinematics, kinetics, electromyography) are presented *1 point*: results of 1 diagnostic tool (kinematics, kinetics, electromyography) are provided *0 points*: no diagnostic tool was applied or associated data are not reported	2	2	2	1
(6) Feedback of target movement speed	*2 points*: angle–time information is provided in real time to the participants by a monitor *1 point*: average cadence provided, e.g., by a metronome *0 points*: no feedback or not reported	0	2	0	0
(7) Consequences of impaired technique	*1 point*: defined consequences (e.g., repeated or excluded from analysis) *0 points*: unclear consequences or not reported	0	1	0	1
(8) Presentation of NHE performance variables	*2 points*: moment–angle or angle–time information (e.g., range of motion to downward acceleration) *1 point*: information about time under tension or range of motion *0 points*: no information available	2	1	2	0
Total ANHEQ SCORE		**4**	**10**	**7**	**6**

Figure 31: The Assessing Nordic Hamstring Exercise Quality rating scale for hamstring testing. Image replicated from Alt & Schmidt (2021).

Table 10: HA*L*HAM° self-evaluation using the Assessing Nordic Hamstring Exercise Quality rating scale for Nordic hamstring exercise testing.

Item	Reference value
Rigid fixation	1
Knee position	2
Kneeling height	1
Separate familiarisation	0
Diagnostic tools	2
Feedback of target movement speed	0
Consequences of impaired technique	1
Presentation of NHE performance variables	2
Total ANHEQ score	**9**

NHE, Nordic hamstring exercise, ANHEQ, Assessing Nordic Hamstring Exercise Quality

5.9 Hardware modifications

Additional updates to the HA*L*HAM° system included hardware modifications. During some earlier NHE trials, a subset of users complained of slippage and a feeling of lack of instability when using the ankle strap variation. This feedback was captured verbally during informal post-trial discussions with participants. While this method does not provide quantitative measures, the consistency of the comments across multiple users highlighted a practical limitation of the original hardware design. These observations informed subsequent modifications to improve heel fixation and overall device stability. Rigid fixation of the heels is an important feature on all hamstring devices as a fixed resistance ensures maximal torque production across the greatest range of motion, and a feeling of safety (Alt et al., 2022; Giacomo et al., 2018). To reflect this limitation, the ANHEQ scale was adapted, awarding only 1 out of 2 points for this criterion. While the scale typically assigns 0 points for partner assistance and 2 points for the rigid fixation, the intermediate score was deemed appropriate to account for the partial compliance with the standards. To address this issue, custom-made hooks were designed, and 3D printed from rigid polymer materials. The hooks provide a stable anchoring point for the participants' heels, replacing the traditional ankle straps, preventing slippage during the NHE, and ensuring that participants can exert maximal force across the full ROM without feeling unstable, or reducing their effort and compromising force reduction (Alt et al., 2022; Alt & Schmidt, 2021a; Giacomo et al., 2018). The 3D printing process allowed precise customisation of hook dimensions to securely accommodate a range of foot sizes, while smooth surfaces and rounded edges prioritised participant comfort. This combination of rigidity, tailored fit, and ergonomic design was to ensure that the hooks maintained both maximal torque production and user safety during testing (**Figure 32**). These hooks are adjustable in position, allowing users to customise their setup for optimal comfort and self-positioning. Additionally, to prevent overextension during the falling phase of the NHE (**Figure 33**), a landing platform was specifically made to accompany the device, as a removable section. This acted as a counterbalance, ensuring stability even with participants of a larger mass, thereby offering an additional layer of safety, and preventing overextension.

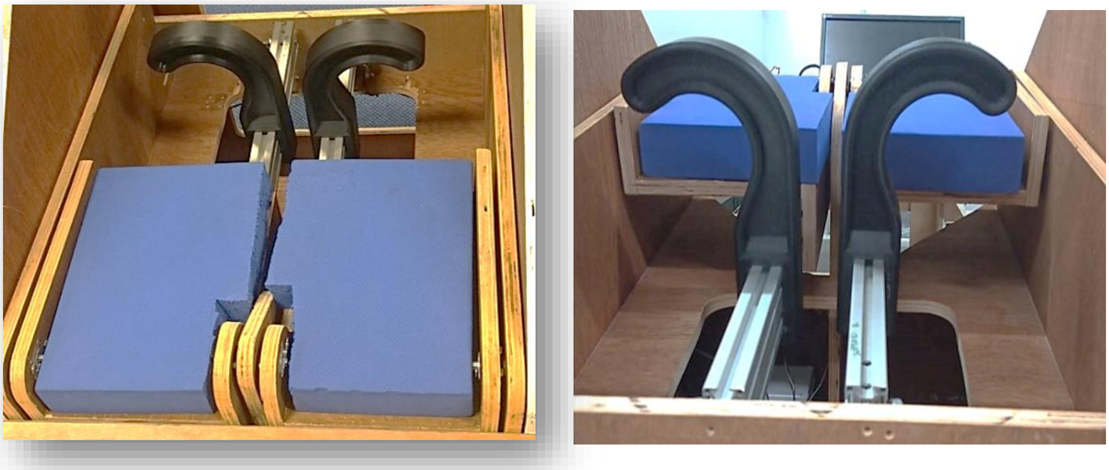


Figure 32: Custom 3D hooks design.

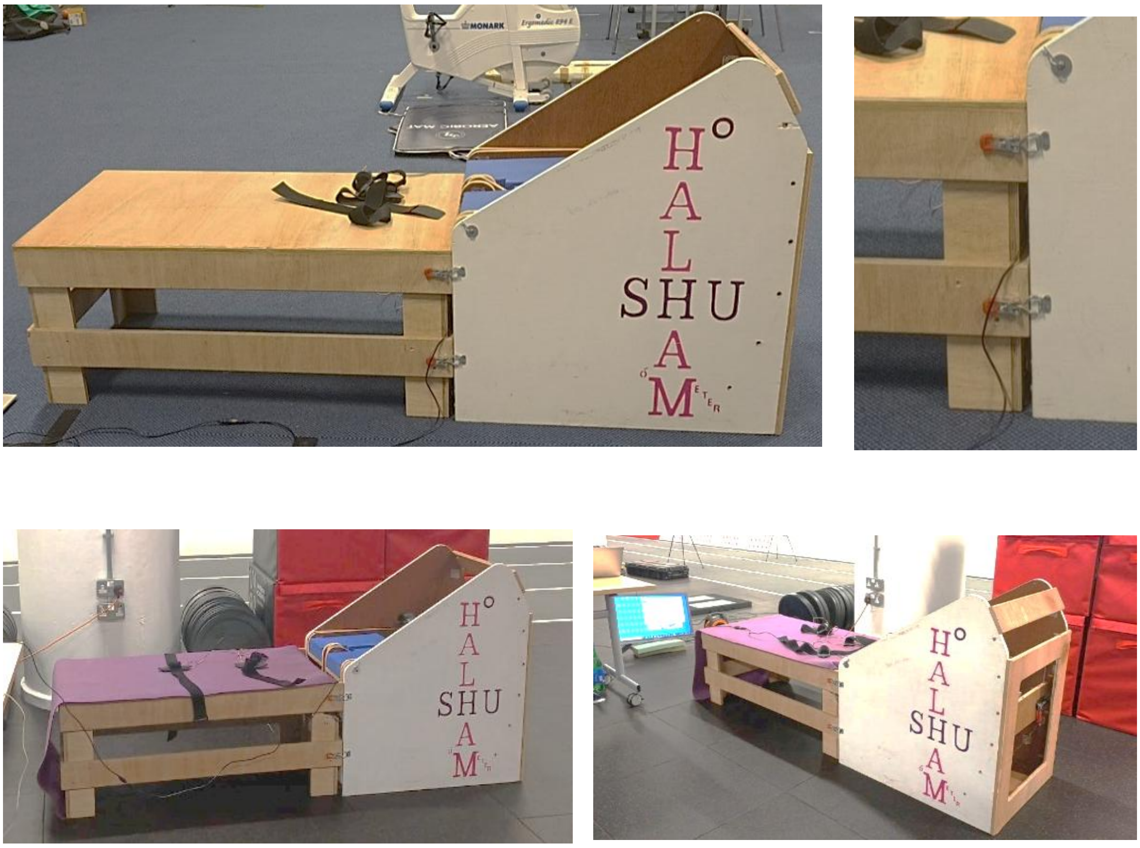


Figure 33: Landing platform removeable section.

5.10 Biofeedback system

A biofeedback system will be utilised to assist participants in tracking their own hip flexion (RTA) and decent speed (AVK) throughout the exercise. To ensure the quality of NHE testing, a constant target movement speed will be incorporated, fulfilling the requirement of the ANHEQ rating scale for NHE testing (Alt et al., 2022; Alt & Schmidt, 2021a). This consistent speed will help standardise the testing method, making it easier to compare results between participants. By maintaining a uniform speed, variations in torque production and muscle activation can be minimised (Bohm et al., 2015; Wiesinger et al., 2020, 2021), leading to a more accurate and reliable assessment of hamstring strength. In addition to maintaining a consistent movement speed, real-time digital feedback on NHE technique, including hip flexion angle, will be provided to participants via a monitor. Feedback has been shown to enhance exercise technique, motor learning, and training adherence by allowing participants to make immediate adjustments (Sigrist et al., 2012; Wulf, 2013). Such mechanisms have been highlighted as important in strength and rehabilitation settings to ensure correct execution and maximise performance outcomes (Concon et al., 2025; Fothergill, 2010). Implementing these measures ensures that NHE testing on the HA*L*HAM° is rigorous, reproducible and aligned with established standards for assessing hamstring function.

5.11 ANHEQ reassessment

Following IMU integration, hardware modifications and the introduction of a biofeedback system, a reassessment of the ANHEQ rating scale now reports an updated score of 13 from a maximum of 13 points for the HALHAM° NHE testing system; subject to separate participant NHE familiarisation (**Table 11**).

Table 11: Updated HA*L*HAM° self-evaluation using the Assessing Nordic Hamstring Exercise Quality rating scale for Nordic hamstring exercise assessment.

Item	Reference value
Rigid fixation	2
Knee position	2
Kneeling height	1
Separate familiarisation	1
Diagnostic tools	2
Feedback of target movement speed	2
Consequences of impaired technique	1
Presentation of NHE performance variables	2
Total ANHEQ score	**13**

NHE, Nordic hamstring exercise, ANHEQ, Assessing Nordic Hamstring Exercise Quality

5.12 Conclusion

Chapter 3 and Chapter 4 identified challenges in controlling NHE descent speed and hip angle, leading to large variability among participants. The ANHEQ assessment has highlighted the importance of incorporating target movement speed feedback as part of the functionality of any NHE assessment. Therefore, it is recommended to implement a feedback system aimed at better controlling NHE technique to help reduce variability between participants and standardise testing results, increasing the validity of the metrics obtained.

Chapter 6

Study 3 –Effect of Biofeedback on Nordic Hamstring Exercise Performance and Technique Metrics.

Elements of this chapter have been published in the article titled, "Examining the effect of verbal feedback vs. real-time software feedback on kinetic and kinematic metrics of the Nordic hamstring exercise" in *Sport Sciences for Health* (https://doi.org/10.1007/s11332-024-01294-6).

This chapter investigates the impact of a software-based biofeedback system (integrated within the HA*L*HAM° device) on NHE technique. The system was designed to monitor hip position and knee extension speed, enabling examination of how feedback influences angular-torque metrics. The agreed-upon NHE performance and technique metrics from **Chapter 3**, together with the newly introduced device modifications described in **Chapter 5,** informed the methodology of this study.

6.1 Chapter aim

The aim of this chapter was to use the HA*L*HAM° biofeedback system to monitor NHE technique and assess its effect on NHE performance and exercise quality metrics.

6.2 Study objectives

i. Implement the IMU-based HA*L*HAM° system with integrated biofeedback software to enable real-time monitoring of NHE technique.

ii. Compare the effects of software-based biofeedback and verbal feedback on NHE performance and technique metrics.

6.3 Hypothesis

i. Using real-time software-based visual biofeedback during the NHE will improve exercise quality by (1) reducing trial-to-trial variability in hip position (RTA at BTA), maintaining values closer to 0° (less hip flexion), and (2) producing a slower and more consistent average descent velocity (AVK) at BTA compared to previous trials without feedback.

6.4 Introduction

A conventional NHE is performed with an athlete assuming a kneeling start position, with the hips fully extended and the torso held upright and rigid (Petersen et al., 2011). From this position, athletes perform a controlled forward rotation action about the knee. In the majority of studies, athletes are informed to gradually lean forward at the slowest possible speed, maximally resisting the forward-falling movement with both legs, whilst holding the hips fixed in line with the knee and shoulder joints throughout the range of movement, keeping a neutral position throughout (Ditroilo et al., 2013; Mjølsnes et al., 2004; Petersen et al., 2011). However, despite its known effectiveness for reducing HSI risk when compliance is high (Goode et al., 2015; Ripley et al., 2021b), concerns remain regarding the reliability of NHE testing, particularly inconsistencies in exercise technique (Alt & Schmidt, 2021a; Cuthbert et al., 2020a; Ditroilo et al., 2013; Pollard et al., 2019).

Quality of execution during the NHE is typically determined by three interrelated factors, the first being *hip position*: excessive hip flexion alters torque demands at the knee and reduces comparability across individuals (Guex et al., 2012b; Hegyi et al., 2019; Pollard et al., 2019). Second is *descent velocity*, which influences both torque production and hamstring activation, and where large variations can undermine test reliability (Alt et al., 2022; Augustsson et al., 2023; Krommes et al., 2021). Third, the presence of a *clear break-point* as this provides an indicator of the muscle length at which the hamstrings reach their torque limit. Previous **chapters (3** and **4)** have highlighted these limitations, reporting high intrasubject variability in both RTA (range=0.4-44.7°), and AVK (range=3.6-

93.4deg·s^{-1}) across 127 NHE trials (n=18). These findings suggest that the reliability of these variables is compromised, reflecting inconsistent execution of the NHE rather than stable measurement error. Such findings emphasise the need for improved methods of standardising and monitoring technique during NHE testing.

In particular, poor control of hip position and descent speed reduces the reproducibility of the exercise and undermines confidence in derived torque metrics (as excessive hip flexion produces larger NHE torque values at the same knee angle compared to a neutral hip position) (Baumgart et al., 2021; Hegyi et al., 2019; Soga, Hakariya, et al., 2023). Hip flexion during the NHE increases the lever arm of the centre of mass about the knee joint axis, which shifts the load onto the knee flexors at longer muscle lengths, potentially moving the torque-generation capacity towards the descending limb of the force-length curve (Hegyi et al., 2019; Šarabon et al., 2019). Therefore, the hip flexion angle should be controlled to allow accurate comparison between athletes (Guex et al., 2012b). Increasing hip flexion lengthens hamstring musculature, as observed in razor curl training (Oliver & Dougherty, 2009), a variation of the NHE in which the athlete begins in a prone position with the hips flexed to approximately 90°. From this position, the athlete moves forward in a controlled manner, simultaneously extending the hips and torso while eccentrically contracting the hamstrings to resist knee rotation (Oliver & Dougherty, 2009; Pollard et al., 2019). However, this exercise does not exhibit a measurable break-point, which is required for assessing the length of the muscle at which failure occurs. A controlled NHE descent, characterised by maintaining a constant angular velocity and avoiding 'breaking' at the hip, ensures that the torques at both the hip and knee are balanced at a given knee angle. Conversely, a rapid increase in hip angular acceleration (or hip 'breaking') can shift the load away from the knee flexors, thereby reducing the torque required to maintain or achieve a specific knee angle (Alt et al., 2022; Augustsson et al., 2023; Krommes et al., 2021).

In the current literature, NHE descent speed has generally been assessed visually and enforced through verbal instruction, using a very slow approach throughout the active range of motion or descending to an average cadence of 30deg·s^{-1} using a metronome (Iga et al., 2012; Marshall et al., 2015; Wiesinger et al., 2020, 2021). AVK influences resultant torque, due to a shift of the torque-velocity relationship and also results in less time for the knee flexors to decelerate and control the forward action. This reduces time-under tension, which is important in NHE training for hypertrophy, specific muscle fibre recruitment, muscular endurance, metabolic stress, and motor unit activation (Wilk et al., 2021). A controlled descent ensuring a maximal break-point is important for determining accurate muscle torque-length capabilities of the knee flexors, such as BTA. A controlled descent should promote recruitment of the hamstring muscle complex, minimising the activity of the accessory muscles such as the gluteus maximus, gastrocnemius, erector spinae, and adductors as suggested by Sconce et al., (2021b). However, further targeted studies are needed to confirm this reduction in compensatory muscle activity. Furthermore, as suggested by Alt & Schmidt, (2021), NHE execution may impede or even prevent adaptations at long hamstring muscle lengths occurring at extended knee angles.

Few studies have considered exercise technique whilst performing the NHE. Alt & Schmidt, (2021) propose clear NHE training execution quality criteria (ANHEQ), recommending that NHEs should be executed with a constant knee extension velocity of 15deg·s^{-1} across the largest possible knee ROM (in a supramaximal unassisted NHE this would be up until ‘break-point’) with a suggested time under tension of ~6.5 seconds per repetition. Moreover, they propose the eccentric phase of the NHE should be performed with minimal hip flexion, keeping the hands situated close to the shoulders, which is typical in the majority of the research (Marshall et al., 2015; Mjølsnes et al., 2004; Park et al., 2019; Raiteri et al., 2021). This provides useful recommendation targets for NHE-assisted training; however, as found in **Chapter 3 and 4** this is difficult to implement for supramaximal NHE testing. It is proposed that integrating a software feedback system for testing can standardise NHE trials (Chalker et al., 2018).

The literature reports that performance can be improved by augmented feedback (feedback from an external source provided as knowledge of performance or result) (Concon et al., 2025; Fothergill, 2010; Lauber & Keller, 2014; Sigrist et al., 2012; Wulf, 2013). This type of feedback is often used during resistance training to enhance acute physical performance and has shown promise as a method for improving chronic physical adaptation (Hopper et al., 2003; Mononen et al., 2003;

Weakley et al., 2023; Wu et al., 2012). However, in the systematic review and meta-analysis by Weakley et al., (2023) it is reported that the magnitude of the response and the optimal method with which feedback is provided is inconsistent between studies. The application of visual and/or verbal augmented feedback, and more recently feedback through visual and/or audible applications (apps) can help increase the rate of learning which may reduce some injury risk factors (Chalker et al., 2018). For example, verbal feedback has been shown to significantly increase eccentric knee flexion force output when traditionally measured on isokinetic dynamometry (Kellis & Baltzopoulos, 1996; Phillips et al., 2013). Most current hamstring testing and training devices offer kinetic feedback in the form of live graphical representation of force or torque traces. They use integrated dashboard software to display performance metrics (Bourne, Duhig, et al., 2017; Bourne, Williams, et al., 2017; Lodge et al., 2020), with results stored on a centralised cloud data storage and analytics platform. Results can be seen in real-time with immediate feedback for metrics such as bilateral hamstring strength, between-limb strength imbalances, and average strength across repetitions (Bourne et al., 2015; Buchheit et al., 2016; Chalker et al., 2018; Opar, Piatkowski, et al., 2013).

However, most NHE studies have only used verbal researcher encouragement or a metronome to control NHE technique such as hip flexion and descent speed, rather than specific computer feedback. Few studies have used visual NHE feedback (Alt et al., 2018, 2023; Chalker et al., 2018; Wiesinger et al., 2021), and very limited studies (Chalker et al., 2018; Weakley et al., 2023) have studied the effect of feedback on NHE metrics, and none to our knowledge examining the effect of *both* kinetic and kinematic feedback on NHE exercise technique metrics. The study by Chalker et al. (2018) examined the effect real-time visual dashboard software feedback had on NHE force outputs, and kinetic metrics such as eccentric knee flexor strength and bilateral force production between limb asymmetries (Chalker et al., 2018). They reported that when feedback was provided on a hamstring testing device there was a significant increase in mean peak force production (mean diff. 21.7N) and no significant difference between limb asymmetry for feedback or no feedback (mean diff 5.7%). The increase in force production with feedback was attributed to an increased weaker limb force contribution compared to the stronger limb (mean diff 15.0N). However, there is little other published literature available regarding the influence of software feedback on NHE kinetic or kinematic metrics. Alt & Schmidt, (2021) state that for NHE intervention studies, standard training procedures should specify a constant target movement speed to get reliable results, and it is recommended to use a monitor to provide angle-time information in real-time to participants.

Therefore, the purpose of this study was to develop a novel, valid, and practically applicable visual feedback system for monitoring NHE execution on the HA*L*HAM° device. The chapter aims to assess the effect of real-time software feedback on NHE exercise quality metrics, specifically RTA at BTA (hip position) and AVK at BTA (knee extension speed), which showed high variability in **Chapters 3 and 4**. It is hypothesised that the software feedback will result in more consistent NHE execution, as indicated by hip flexion closer to 0° at BTA, slower AVK at BTA, and reduced CV% compared to previous chapters, reflecting improved within–session reliability of the previously variable technique metrics.

6.5 Methods

The HA*L*HAM° NHE custom device was used to collect the data (Sconce et al., 2021a, 2021b). Strain gauge load cells (DYMH-103 Micro Miniature Load Cell) measured individual right and left limb forces, and the software displayed these and combined limb total forces as force-time traces in line graph format. Torque was calculated for each NHE trial from the force measured by the load cells and the distance measured from the set pivot point (0.661m).

The software feedback was a custom-made visual system using an on-screen mannequin representation of a person and a pre-determined reference line to provide visual cues for the user (**Figure 34**). The IMU sensors tracked the user's knee and hip flexion angles in real time and used these to animate the mannequin. The superimposed dynamic reference line extended from the mannequin's lateral epicondyle through the greater trochanter, to the shoulder bursa. The IMU measurements from the sensors have been validated against a gold-standard Polhemus motion capture system (**Chapter 5**), demonstrating very strong correlations (r^2>0,98) and minimal bias in Bland-Altman analysis, confirming that the system provides accurate and reliable angular kinematic data for real-time visualisation.

NHE movement velocity should be relatively slow at 4-6 seconds across approximately 90° flexion (Alt et al., 2022; Alt & Schmidt, 2021a; Brazier et al., 2019). A controlled descent allows the hamstrings to generate high eccentric force potential, stimulating tendon stretch and subsequent neuromuscular adaptations (Brazier et al., 2019). Therefore, the target speed was set at $20 deg \cdot s^{-1}$, which corresponds to a 4-5 second descent and aligns with NHE velocities reported in the literature (Alt et al., 2023; Crawford et al., 2023). Hip flexion was set at 0° to encourage a neutral position throughout the range of motion. As the user performed the NHE action, they were prompted to match the movement of the reference line with the virtual representation on-screen. A monitor was positioned on a stand on the floor, at the base of the HA*L*HAM° platform to suit the eye-line position. The grey reference line warned the user of deviation from the set optimal hip angle and speed by turning orange as a warning if within a range of 5° and then red if greater than 5° from the set coordinates (**Figure 34**).

Figure 34: Illustration of the custom-made visual feedback system and on-screen mannequin with reference line. The moving reference line turns orange (a) as a warning if within a range of 5° and then red if greater than 5° from the set coordinates.

Raw IMU data was acquired on a personal computer via a Phidget Bridge data acquisition board (Phidgets Inc., Calgary, Canada). The IMU data were converted into angles using a custom-coded program implementing a complementary filter and then exported in .CSV format. Using MATLAB R2022b software (MathWorks, Inc., Natick, MA) the following variables were subsequently calculated using a custom script:

Injury risk metrics as proposed in **Chapters 3 and 4:**

- **Peak torque** ~ NHE bilateral maximum torque value (calculated by summing the peak torque recorded for each limb).
- **Break-torque angle (BTA)** ~ representing the knee and corresponding thigh angle at the instant that peak torque occurred. Full extension is represented as 180 degrees.
- **Bilateral limb torque difference (BLD)** ~ representing the percentage difference between the right and left leg maximum torque values.

Exercise quality metrics as proposed in **Chapters 3 and 4**:

- **Relative trunk-to-thigh angle (RTA)** ~ the angle in the sagittal plane between the thigh and the trunk throughout the NHE ROM, representing hip angle. RTA at peak torque is then determined. A higher RTA value corresponds to a greater degree of hip flexion, while a lower value indicates a more neutral position.
- **Angular velocity of the knee joint (AVK**) ~ representing the angular velocity of the knee joint throughout the NHE ROM, filtered using an 11-point average. AVK at peak torque is then determined.

6.5.1 Participants

Twenty-four recreationally active participants (n=24) of varying NHE training experience, gender, and age were recruited to participate in this study (Mean ± SD age 29 + 11years, height 177 ± 8.3cm, and body mass 78.6 ± 14.1kg). With respect to NHE familiarity, participants ranged from no prior exposure (n=10) to limited experience through team warm-ups or rehabilitation settings (n=9), to regular use as a part of a structure strength training (n=5). With exercise technique being the feedback focus, and this being explanatory research, a diverse representation of participants was chosen to offer a more holistic understanding of technique challenges and feedback impact. A sample size of 24 is comparable to other NHE crossover design studies by Chalker et al., (2018), Krommes et al., (2021), Jorge et al., (2024) and Walsh, O'Brien and Browne, (2024) where the participant range was between 8-44. A post-hoc power analysis for a sample size of 24 participants, with an alpha level of 0.05 and an estimated effect size of 0.5 (medium) indicated a statistical power of 77%. A medium effect size was selected as the expected magnitude of change because previous biomechanical intervention studies using real-time visual feedback have typically reported effects of this scale when improving kinematics and exercise technique consistency (Alt & Schmidt, 2021a; Chalker et al., 2018; Weakley et al., 2023) . This assumption was therefore considered realistic and practically meaningful, reflecting moderate but functionally relevant improvement in NHE execution quality rather than large-scale performance adaptations.

Exclusion criteria included a lower extremity injury in the previous 6 months requiring medical intervention or that caused significant functional impairment. Participants were also excluded if they reported a history of recurrent low-back, hip, thigh, or knee injuries. This refers to multiple episodes of an injury, including any injuries that restricted physical activity or pain during exercise for more than 2 consecutive weeks on 2 or more occasions within the last 6 months. Furthermore, all participants self-declared as being physically fit and free from any health or medical conditions that would contraindicate or impede them from performing maximal NHE testing. After having all procedures explained to them, participants provided written informed consent to participate in the spirit of the Helsinki Declaration, before testing commenced. Ethical approval for the study was approved by the Universities Ethics Committee (ER29609708).

6.5.2 Procedures

Prior to performing the trials participants were instructed to perform an individual warm-up by using a stationary bike or rower for 3-5 minutes and completing dynamic movements such as arm and hip circles, leg swings, heel-to-toe walks, knee hugs, walking lunges, and squats (2 sets of 10 repetitions). Participants' NHE starting position was determined by lining up the lateral femoral epicondyle of the femur with the pivot point before commencement (Sconce et al., 2021b) . An IMU (MOT1101, Phidgets Inc., Calgary, Canada) was positioned on a custom-made plastic carrier with pointed ends to help align the sensor laterally on the upper leg at an equal distance away from the greater trochanter and lateral femoral epicondyle. The IMU trunk sensor was also positioned laterally at an equal distance from the greater trochanter to the shoulder bursa. The IMU device had a data acquisition rate of 41.67Hz. For the verbal feedback condition, the researcher instructed participants to gradually lean forward at the slowest possible speed maintaining a neutral trunk alignment with the hips fixed in line with the knee and shoulder joints whilst holding the hands in line with the shoulders, palms facing forward (Mjølsnes et al., 2004). Avoidance of lumbar hyperextension was also advised. This method was applied consistently across all chapters to ensure methodological uniformity. Participants were asked to perform the NHE action until they could no longer withstand the torque around their knee flexors, using their hands to buffer the fall onto a fixed platform (Petersen et al., 2011; Sconce et al., 2015).

A crossover randomised design was used so that all participants received verbal instruction *and* real-time software feedback on NHE technique over 2 separate sets of 3 maximal repetitions (6 maximal repetitions overall). The rest period between repetitions was standardised at approximately ~6s, which has shown to provide sufficient recovery for repeated maximal efforts during sets of 3 NHE repetitions (Alt & Schmidt, 2021a). Participants were instructed to wait for the researcher's verbal cue before commencing the next repetition ensuring consistency across all trials. The rest period between feedback types was substantial, at least 15 minutes, allowing for complete recovery (Örer et al., 2016). The order of performing the feedback (either verbal feedback or software feedback first) was randomised among participants using a research randomiser website, with participants assigned numerical identifiers.

6.5.3 Statistical analyses

144 trials from 24 participants (n=24) were initially considered (72 trials for each feedback condition). Data from the HA*L*HAM° IMU's were treated in MATLAB R2020b software (MathWorks, Inc., Natick, MA) and the data was subsequently statistically processed in GraphPad Prism 8.43 (GraphPad Software Inc). Trial exclusion criteria were no clear peak in the force-time trace, an extended flattened period, or no clear torque drop-off period; no trials were rejected. Descriptive statistics for all trials were calculated and reported as mean ± standard deviation (**Table 12**). Normality of data was confirmed using the Shapiro-Wilk test and a visual check of Quantile-Quantile plots. Data for each participant were averaged across 3 trials per condition. This approach provides a stable estimate of individual performance while reducing the influence of trial-to-trial variability or isolated extreme values. Outliers were identified using the ROUT method (Q=1%). When analysed separately for each feedback condition no outliers were detected. Two outliers were flagged when all participant means were pooled across both conditions; however, because the main analyses compare conditions within participants, the separate-condition approach is most appropriate, and no data were excluded.

Paired-samples t-tests were the used to assess the effect of feedback condition (verbal feedback vs. software feedback). Metrics compared were peak eccentric knee flexor torque (Nm), BTA (°), BLD (%), RTA (°) at peak torque, and AVK ($deg \cdot s^{-1}$) at peak torque. Effect sizes were calculated using Cohen *d* and interpreted as small ($d \geq 0.2$), moderate ($d \geq 0.5$), and large ($d \geq 0.8$) (J. Cohen, 2013). Statistical significance was set at $p<0.05$ for all analyses. Results were reported as test statistics in the following format: test statistic (df) = value, p = …, effect size = …. In addition to mean differences, within-session variability (CV%) was calculated for all metrics to determine whether the introduction of real-time feedback improved measurement consistency.

6.6 Results

Descriptive statistics for each metric per feedback condition are shown in **Table 12** and reported as mean ± standard deviation. The variability for each metric is reported as the minimum to maximum value range. **Table 13** reports the corresponding CV% for each metric per feedback condition. Performance and injury-risk metrics (peak torque, BLD and BTA) are shown in **Figure 35** illustrating any significance between feedback conditions. NHE technique metrics (AVK at BTA, and RTA at BTA) are shown in **Figure 36** illustrating any significance between feedback conditions.

Table 12: Mean, standard deviation, and range reported for each metric per feedback condition (n=24).

	Verbal Feedback		**Software Feedback**	
Metrics	Mean ± SD	Range (Min-Max)	Mean ± SD	Range (Min-Max)
Kinetics				
Peak torque (Nm)	79.7±31.4**a*	32.7-148.4	72.6±27.9**a*	36.2-142.1
Kinematics				
BLD (%)	10.8±6.4	2.9-30.6	11.2±6.5	4.2-29.9
BTA (°)	118.8±9.8	102.0-141.3	120.3±9.1	106.5-146.2
RTA (°) at peak-torque	22.1±13.2**b*	1.7-57.9	16.4±8.7* *b*	2.3-34.6
AVK ($deg \cdot s^{-1}$) at peak-torque	24.6±13.5**c*	5.8-61.6	15.9±5.9* *c*	3.5-26.7

Nm, Newton-metre, %, percentage difference, °, degrees, $deg \cdot s^{-1}$, degrees per second, BLD Bilateral limb torque difference, BTA Break-torque angle, RTA Relative trunk-to-thigh angle, AVK Angular velocity of the knee

*denotes a significant difference between verbal feedback and software feedback ($p<0.01$)

a denotes a small effect size, *b* denotes medium effect size, *c* denotes large effect size

Table 13: CV% calculated from the 3 raw trials per participant (n=24), per condition, then averaged across participants.

Metrics	**Verbal Feedback CV%**	**Software Feedback CV%**
Kinetics		
Peak torque (Nm)	39.4	38.4
Kinematics		
BLD (%)	59.2	58.0
BTA (°)	8.3	7.6
RTA (°) at peak-torque	59.8	53.0
AVK ($deg \cdot s^{-1}$) at peak-torque	55.2	36.8

Nm, Newton-metre, %, percentage difference, °, degrees, $deg \cdot s^{-1}$, degrees per second, BLD Bilateral limb torque difference, BTA Break-torque angle, RTA Relative trunk-to-thigh angle, AVK Angular velocity of the knee

6.6.1 Injury risk factor metrics

Eccentric knee flexor peak torque demonstrated high variability, with CV% reducing marginally when using software feedback, from 39.4% (verbal) to 38.4%. Similarly, BLD showed high variability, with CV% decreasing slightly from 59.2% (verbal) to 58.0% (software). BTA variability was low across both feedback conditions (8.3% verbal vs. 7.6% software) (**Table 13**). Eccentric knee flexor peak torque significantly decreased with software feedback compared to verbal feedback, $t(23)=3.13$, $p<0.01$, $d=0.238$, showing a mean reduction of 7.1Nm. Altering feedback had no significant effect on BLD, $t(23)=0.56$, $p=0.58$, $d=0.07$, or BTA, $t(23)=1.64$, $p=0.12$, $d=0.16$ (**Table 12** and **Figure 35**).

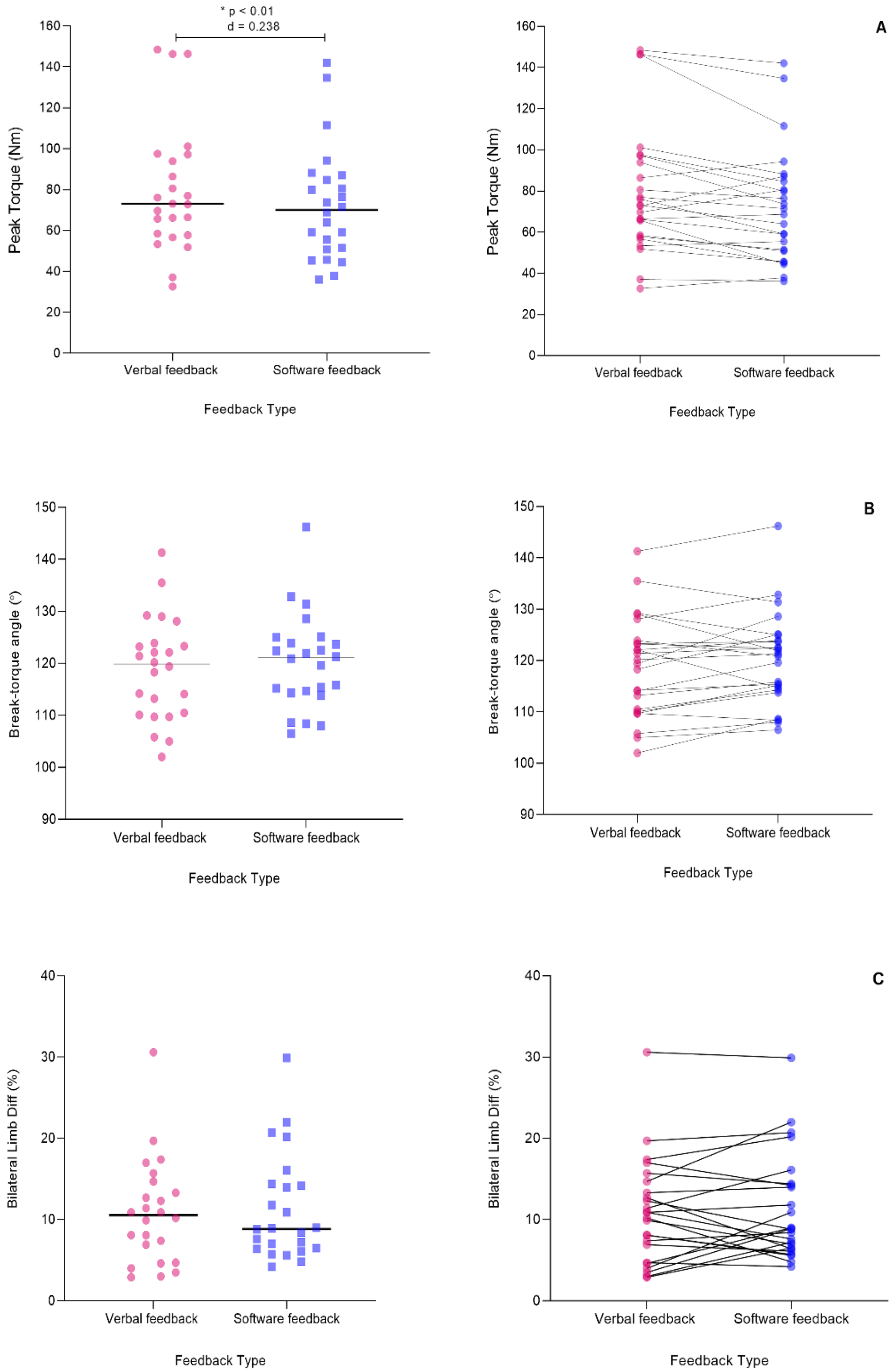


Figure 35: Eccentric knee flexor peak torque (A), break torque angle (B), and bilateral limb difference (C) performance metrics for verbal feedback (n=24) and software feedback (n=24) conditions. Asterisks (*) indicate any significant differences between feedback conditions.

6.6.2 Exercise technique metrics

RTA demonstrated high variability, with CV% decreasing from 59.8% (verbal) to 53.0% when using software feedback. AVK variability reduced notably, with CV% decreasing from 55.2% (verbal) to 36.8% (software) (**Table 13**). RTA significantly decreased with software feedback, t(23)=2.98 $p<0.01$, d=0.51, showing a mean decrease of 5.7° compared to verbal feedback. AVK significantly decreased with software feedback, t(23)=3.67, $p<0.01$, d=0.825, showing a mean decrease of 8.7 deg·s^{-1} compared to verbal feedback (**Table 12** and **Figure 36**).

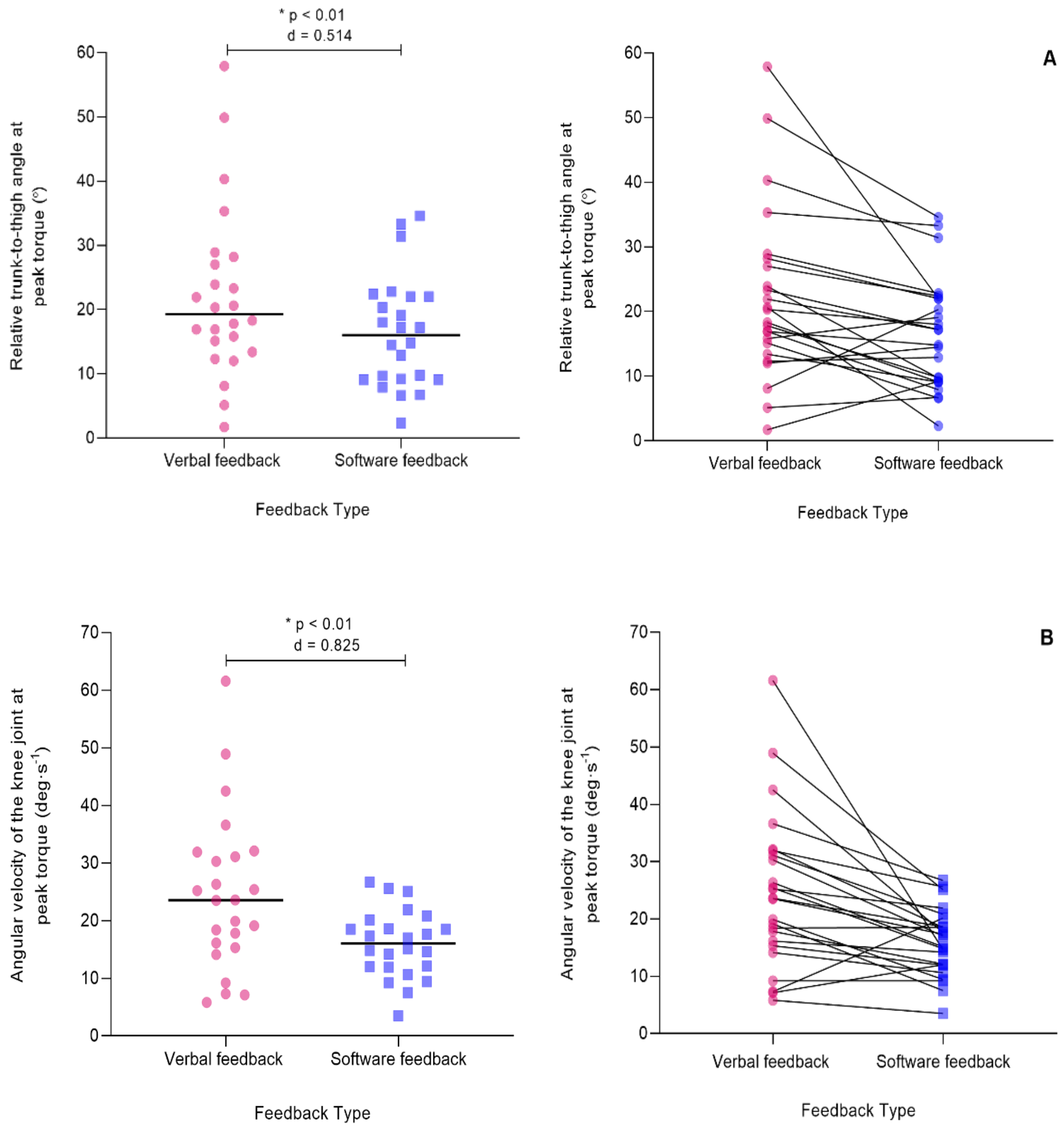


Figure 36: Relative trunk-to-thigh angle (A) and angular velocity of the knee joint (B) at peak torque technique metrics for verbal feedback (n=24) and software feedback (n=24) conditions. Asterisks (*) indicate any significant differences between feedback conditions.

6.7 Discussion

The findings affirm the hypothesis that real-time software-based feedback improves acute NHE exercise quality by reducing hip flexion variability and promoting a slower, more consistent descent. These results align with the systematic review findings by Weakley et al., (2023) who reported that resistance training feedback has a positive influence on immediate performance and can improve favourable adaptations over the long term. Both technique metrics assessing hip flexion (RTA) and movement velocity (AVK) significantly improved with software feedback (**Table 12** and **Figure 36**). However, performance metrics demonstrated either no significant change or a significant decrease (peak torque) when using software feedback (**Table 12** and **Figure 35**). BLD percentage and BTA showed no significant change between feedback conditions and peak torque significantly decreased with software feedback by a mean decrease of 7.1Nm compared to verbal feedback. This finding was unsurprising as eccentric contractions typically show that higher velocities (AVK) lead to greater force production (Hody et al., 2019). However, in the case of a controlled NHE action, where a slower, constant descent speed and a neutral hip position are maintained, the torque-velocity relationship is altered. Reduced movement velocity results in less torque, producing a left-ward shift in both the torque-length and torque-velocity relationships (Augustsson et al., 2023; Pollard et al., 2019). The periods of acceleration observed during the NHE likely reflect the onset of task failure with acceleration due to gravity. Moreover, the software feedback in this study was intentionally confined to modify NHE hip flexion and speed exclusively and not directly impact injury risk factor metrics. Interestingly the upper ranges dropped significantly (**Table 12** and **Figure 36**) with software feedback for both RTA (57.9° to 34.6°) and AVK (61.6deg·s^{-1} to 26.7deg·s^{-1}), which suggests that individuals initially exhibiting poorer exercise technique showed the most improvement, thereby reducing inter-individual variability, and bringing them closer to the ranges of 0° hip position and a slower AVK at BTA. This is further supported by the lower CV% for RTA and AVK under software feedback (**Table 13**), indicating improved within-participant consistency across repeated trials. In **Chapter 4**, CV% values for RTA (51.0-64.7% across inclinations) and AVK (60.5-92.2% across inclinations) were higher than in this study, demonstrating that real-time feedback can enhance consistency.

The literature shows the impact of different hamstring exercises on muscle architecture and morphology and the implications this can have for injury prevention (Baumgart et al., 2021; Bourne, Williams, et al., 2017; Kellis & Blazevich, 2022). Notably, Baumgart et al., (2021a) reported that parametric and angle-specific flexion and extension torques differ according to hip flexion, velocity, and muscle contraction mode. Hamstring muscles operate differently across different lengths in response to changing exercise stimuli (Kellis & Blazevich, 2022) and studies have suggested that injury is associated with a left-ward shift of peak torque to shorter angle lengths in the hamstrings (Brockett et al., 2004). The evaluation of the torque-angle relationship may be a useful tool for predicting hamstring strain injuries and as a return-to-play measure (Andrews et al., 2025; Guex et al., 2016; Kellis & Blazevich, 2022; Maeo et al., 2021; Tyler et al., 2017). Therefore standardised, controlled technique of exercises that measure torque-angular data is important, as a deviation of form can alter the intended nature of the exercise, impacting the desired adaptations, whether for training, angle-specific testing, performance optimisation, injury prevention or rehabilitation. Specifically, in the NHE, maintaining a neutral 0° hip position minimises variability in torque production, allowing for a more consistent and targeted training effect in the knee flexor muscles, however whether this enhances the overall training effect depends on the specific adaptation being targeted, and further research is required (Van Hooren et al., 2022; Walsh et al., 2024). For NHE training interventions and testing, maintaining controlled technique (hip flexion and descent speed) is needed to understand the mechanisms driving observed adaptations to better inform practitioners. Software feedback can assist in ensuring proper form throughout the exercise, therefore supporting more consistent and reproducible movement patterns within a session, rather than increasing measurement reliability.

Chalker et al., (2018) reported an increase in mean peak force production when using feedback, however it was specific to force-time traces on a screen and not hip and knee angles, or movement velocity. Moreover, if increased torque is a result of suboptimal exercise technique, there is a risk of overestimation which has implications in hamstring training intervention studies where precise quantification of change is important for assessing the effectiveness of the intervention (Amundsen et al., 2023). Additionally, the production of peak torque within a shorter muscle length range is less useful for targeting the site of hamstring injuries (Brockett et al., 2004; Guex et al., 2012b). It is, therefore, reasonable to hypothesise that integrating software feedback into chronic NHE training, using a moving reference line on-screen and supplementing it with the option to visualise torque-time traces and break-point failures as part of a performance/injury-risk software mode would be beneficial.

Several advantages of the biofeedback system include immediate user correction, engagement, and better exercise technique. The system reinforces proper NHE form by visually guiding users through the correct range of motion and pace (Alt et al., 2022; Alt & Schmidt, 2021a). Real-time visual feedback has been shown to improve motor learning, enhance exercise adherence, and reduce technical errors by providing immediate knowledge of performance (Concon et al., 2025; Sigrist et al., 2012). Such feedback mechanisms help participants avoid overextension or rapid movements that could lead to strain on the hamstrings (Alt & Schmidt, 2021a; Bourne, Williams, et al., 2017). As users receive immediate visual cues, they can make adjustments allowing them to course-correct during the exercise. The visual representation and reference line create an interface experience, encouraging users to maintain focus and adherence, which is a major issue in NHE compliance (Van Der Horst et al., 2021). It is suggested that acute feedback is most beneficial when of high frequency (during every rep), and of a visual kinematic nature (Keller et al., 2014; Weakley et al., 2023), which the HA*L*HAM° software feedback system offers.

Limitations of the study include the relatively modest sample size, and the absence of a separate pre-testing familiarisation phase as noted in (Alt & Schmidt, 2021a). Nonetheless, the primary focus was on examining changes in technique metrics with software feedback rather than preparing athletes for exhaustive performance testing or training. User feedback, collected informally through verbal comments made by participants immediately after the testing, recommended that the reference line start from a position behind neutral. Specifically, participants suggested beginning with a slightly flexed knee position with a ‘preliminary movement phase’ to allow the user to adjust to the pace before passing through the neutral position (**Figure 37**). As a result, the test should then be initiated in a manner that ensures a controlled and smoother commencement. These suggested modifications are recommended for future iterations of the system to improve usability.

Another consideration for software feedback adjustment would be defining an anatomically aligned hip flexion angle reflecting natural physiological curvature of the lumbar spine, within a permissible range of up to 20° as suggested by Alt & Schmidt, (2021). This modification would expand the cautionary orange range to encompass values up to this threshold and subsequently set the red range beyond it. Alt & Schmidt, (2021) recommend NHEs should be executed with a constant knee extension velocity of 15deg·s^{-1} across the NHE range of motion, with a 10deg·s^{-1} deviation of this being classed as the break-point (failure). Again, setting a cautionary range for knee extension velocity of between 15 - 25deg·s^{-1} should be explored in future work.

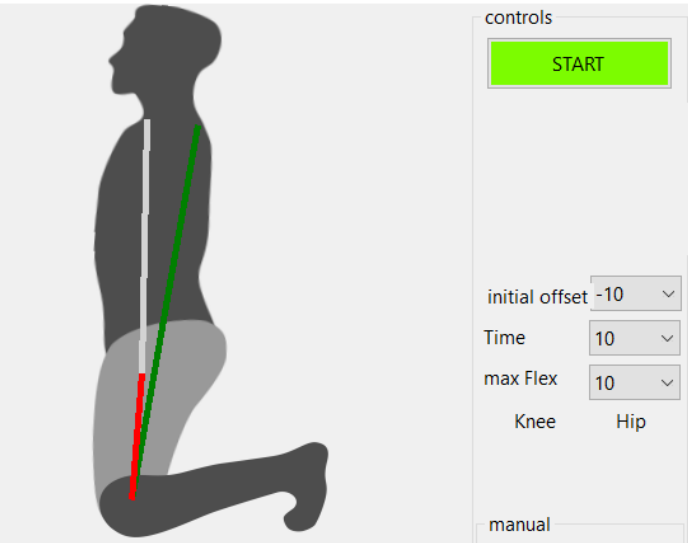


Figure 37: Conceptual illustration of the proposed updated feedback system, featuring an on-screen mannequin with a preliminary movement offset reference line. This modification was suggested by participant feedback after testing but was not implemented in the version of the HA*L*HAM° software used in the present study.

Implementing a flexible software feedback system for NHE training where the individual could customise the AVK and RTA threshold, would be advisable. This would support the required muscle adaptations required for personalised hamstring training. For instance, faster eccentric loading velocity could be advantageous for recruiting higher hamstring muscle activation (Augustsson et al., 2023; Krommes et al., 2021; Zehr & Sale, 1994), whereas a slower velocity with controlled hip flexion might be preferable for optimising time-under-tension, without using the accessory muscles to maximise the preferential protective adaptations of hypertrophy and longer BF_{LH} fascicle length required for HSI prevention (Augustsson et al., 2023; Bourne, Williams, et al., 2017; Timmins, Bourne, et al., 2016). Ongoing user familiarisation of the feedback system over the long term would be required to evaluate its effectiveness for this type of purpose.

6.8 Conclusion

The HA*L*HAM° integrated biofeedback software system significantly improves acute NHE exercise technique quality, as reflected by significant reductions in hip flexion and descent velocity. These benefits were particularly evident among participants who initially demonstrated greater deviations from the desired NHE technique (excessive hip flexion and an inconsistent faster descent velocity at BTA), suggesting that the system particularly benefits those individuals requiring greater assistance to maintain correct form. This effect reflects participant exercise technique performance differences rather than limitations or unreliability of the device.

6.9 Chapter conclusion statement

It is recommended that hamstring device testing should include measurements of both BTA and maximal torque, with NHE technique monitored by a feedback system to reduce variability and improve standardisation across participants and studies. This recommendation is supported by the lower CV% values observed for software feedback compared to verbal feedback in both this study and

Chapter 4. RTA and AVK measurements should be captured to assess the long-term effectiveness of using a feedback system in improving exercise technique. Having improved and standardised the HA*L*HAM° device for testing, it is now important to explore its capability to assess muscle activation patterns and evaluate torque-length relationships, alongside associated kinetic and kinematic metrics as an integrated system. These insights will be critical for establishing the incline NHE as a potential preventive measure against HSIs and as a rehabilitation protocol. Furthermore, it will provide a comprehensive framework for understanding the HA*L*HAM° system in its finalised optimised form, demonstrating its utility as a versatile and robust tool for research and practical application.

Chapter 7

Study 4 – A Cross-Sectional Study Investigating Muscle Activity During Incline Nordic Hamstring Exercise Testing.

This chapter investigates whether the inclined variation of the NHE elicits greater BF_{LH} muscle activity in the proximal range compared to the conventional flat NHE. This comparison aims to establish whether the incline variation can offer enhanced relevance for HSI prevention and rehabilitation, particularly for end-range hamstring conditioning. Surface EMG was used to record muscle activation patterns in both conditions. The study design incorporated the agreed-upon NHE performance and technique metrics established in **Chapter 3**, the device modifications introduced in **Chapter 5**, and the biofeedback software system developed in **Chapter 6**, ensuring a comprehensive and standardised approach to the data collection.

7.1 Chapter aim

The aim of this chapter was to compare the kinetics, kinematics and muscle activation patterns of the flat and incline NHE conditions.

7.1.1 Study objectives

i. Compare hamstring muscle activation patterns between flat and incline NHE conditions.

ii. Determine whether the incline NHE preferentially activates the BF_{LH} at longer muscle lengths.

7.1.2 Hypothesis

i. The incline NHE will elicit greater BF_{LH} activation at longer muscle lengths compared to the flat NHE.

7.2 Electromyography activity and hamstring injury

Most injuries occur in the hamstring proximal region, which coincides with the point of greatest muscle elongation (Mendiguchia et al., 2015; Woods et al., 2004), suggesting that the hamstring being in a lengthened state may be a precursor to injury. Furthermore, research indicates that EMG activity of the BF_{LH} muscle peaks during the late-swing phase of sprinting, coinciding with the peak length of the muscle (Higashihara et al., 2015, 2018). During this critical phase, the BF_{LH} needs to tolerate forces ranging between 10.5-26.4 $N.Kg^{-1}$ (Kenneally-Dabrowski, Perriman, et al., 2019), reaching 110% of its maximum resting length, whilst experiencing its highest levels of excitation (Thelen et al., 2005). This dynamic is thought to represent the possible mechanism of HSI occurrence.

Several studies have reported a gradual decrease in BF_{LH} EMG activity after the BPA in the NHE (Keerasomboon et al., 2022; Soga, Hakariya, et al., 2023). A greater BPA, achievable by utilising an incline NHE as opposed to the flat variation (Sconce et al., 2021b) suggests that peak activation of the BF_{LH} could be preferentially attained at a more favourable longer length within the proximal hamstring range. A recent study by Soga, Hakariya, et al., (2023) supports this theory, demonstrating that incline NHE testing resulted in sustained high activation of the BF_{LH} while concurrently reducing ST activation compared to the flat Nordic variation. This preferential recruitment of the BF_{LH} at an extended muscle length could be beneficial for injury prevention and rehabilitation outcomes. Furthermore, Soga, Yamaguchi, et al., (2023) observed no significant difference between the BPA of the NHE, measured using a smartphone application (Nordic Angle app) and the knee flexion angle at peak BF_{LH} EMG activity ($d=0.13$, $p=0.678$) supporting its validity for identifying the point of eccentric failure. Moreover, at 20-25° after BPA, BF_{LH} activity was significantly lower ($d=0.87$, $p=0.011$), further reinforcing the applications ability to capture meaningful changes in hamstring loading. While initial evidence supports the applications validity, further work would be needed to confirm its reliability across repeated testing. As a preventative measure against HSI, it is therefore recommended to incorporate knee flexion exercises in intervention programmes that enhance BF_{LH} EMG activity at 145-165° of knee flexion (when full extension is 180°). The BPA is approximately 130° even in trained soccer players (Lee et al., 2018), and therefore BF_{LH} EMG is likely diminished by 145° in a conventional flat NHE (Ditroilo et al., 2013; Monajati et al., 2017). Incline NHE training is proposed as a more effective approach to achieving this angle, potentially optimising muscle activation.

7.3 Bicep femoris long head – semitendinosus relationship

The NHE has shown to elicit high levels of BF_{LH} activity, suggesting it can serve as an effective stimulus for adaptation within this most commonly injured muscle (Timmins et al., 2015). However, studies have consistently reported that the ST muscle is preferentially activated during the NHE compared to other individual knee flexor muscles (Bourne et al., 2016; Bourne, Williams, et al., 2017). Therefore, the dynamic relationship between the BF_{LH} and ST is particularly important and warrants further investigation to better understand its implications for training adaptations. Performing the NHE on an incline should increase the activation ratio of the BF_{LH} relative to the ST (Keerasomboon et al., 2022; Soga, Hakariya, et al., 2023). This modification places greater emphasis on knee flexion at extended knee angles, potentially training the BF_{LH} to control torques more effectively in its proximal range of motion (Park et al., 2019; Šarabon et al., 2019). Greater recruitment of the BF_{LH} at extended muscle lengths, coupled with the nuanced interplay between the BF_{LH}-ST should lead to preferential adaptations in the knee flexors (Marušič et al., 2020; Šarabon et al., 2019; Sconce et al., 2021b; Tyler et al., 2017). Conversely, performing the NHE on a decline may shift activation towards the ST, potentially improving its fatigue resistance and reducing compensatory BF_{LH} activation during eccentric contractions (Ripley et al., 2024; Šarabon et al., 2019; Sconce et al., 2021b). A clearer understanding of this multifaceted relationship could help practitioners refine return-to-play protocols, optimise hamstring training strategies, and develop targeted intervention for effective rehabilitation and injury prevention (Guex et al., 2016; Kellis et al., 2017; Maeo et al., 2021; Schuermans et al., 2014).

7.4 Electromyography measurement

EMG is a neuromuscular assessment method that involves the process of recording the electrical activity of muscles. Through measuring the electrical signals generated during muscle contractions by motor units inside muscular tissue, EMG offers valuable insights into neuromuscular function and coordination (Al-Ayyad et al., 2023). Surface EMG (sEMG) enables the recording of comprehensive muscular potential signals from multiple muscle groups, offering a broader assessment of an entire muscular region rather than focusing solely on a single motor unit. Responses include data on muscle activation, fatigue levels and synchronisation patterns (del Toro et al., 2019; Campanini et al., 2020; Al-Ayyad et al., 2023). Using sEMG eliminates the need for invasive electrodes, thereby avoiding participant discomfort and minimising the risks associated with testing (Fang et al., 2020; Konrad, 2006).

EMG is commonly used to assess the activity of the individual hamstring muscles during the NHE (Bourne et al., 2016; Bourne, Williams, et al., 2017; Delahunt et al., 2016; Krommes et al., 2021; Vicente-Mampel et al., 2022; Yu et al., 2008). It has been used to understand the impact of muscle activation patterns in reducing the risk of HSIs and minimising their recurrence (Khairunnisa et al., 2023; Opar, Williams, Timmins, et al., 2013) . Additionally, EMG provides valuable insights for informing hamstring training practices, targeted intervention protocols and guiding effective rehabilitation strategies (Ditroilo et al., 2013; Fyfe et al., 2013; Hegyi et al., 2018, 2019; Kellis et al., 2012; Krommes et al., 2021). Quantifying ST activation alongside BF_{LH} is particularly important, as the ST serves as a support muscle for generating eccentric force during the NHE. Research by Bourne, Williams, et al., (2017) highlights the ST's contribution to eccentric hamstring strength, finding that in the uninjured limbs of men with a history of unilateral HSI (n=10), the ST exhibited percentage increases in transverse relaxation times with exercise that were 16.8%, 15.8%, and 20.2% greater than those observed in the BF_{LH}, bicep femoris short head and semimembranosus muscles, respectively ($p<0.002$ for all). Incorporating muscle activity data for both the BF_{LH} and ST could help provide better insight into the functional role of the ST in eccentric force production, and its potential to redistribute load among the hamstring muscles, thereby reducing strain on the BF_{LH} which could mitigate the risk of HSI injury.

7.4.3 Angle specific muscle activation measurement

Typical EMG measures include peak EMG, integrated EMG (iEMG) and Rate of Rise (RoR). These metrics have been reported to provide valuable insight into muscle function and performance, guiding training and recovery protocols. Peak EMG represents the maximum electrical activity during a movement or contraction offering an indication of the muscle's activation intensity. iEMG measures the cumulative electrical activity over time, reflecting the total muscle workload. RoR quantifies the speed at which muscle activation increases, highlighting neuromuscular response times and dynamic strength capabilities (Ripley et al., 2024).

Focusing on joint angle-specific activation during the NHE may be a more beneficial approach than using time-based EMG measurement (D. Cohen et al., 2015; Kellis & Blazevich, 2022). The NHE involves muscle activation that varies with changes in joint angles, and time-based EMG does not account for the dynamic changes in muscle length and joint mechanics during the NHE, missing critical angle-specific details that are biomechanically significant (Alt et al., 2023; Kellis & Blazevich, 2022; Park et al., 2019). Therefore, measuring activation at specific angles aligns more closely with the biomechanical demands on the knee flexors, particularly during NHE eccentric contractions where injury mechanisms are more likely to occur (extended knee angles) (Guex et al., 2016; Hirose et al., 2021; Marušič et al., 2020). Angle-specific EMG captures data on the points where the hamstrings are under peak eccentric load, which is essential for injury prevention and targeted training (Hirose et al., 2021; Keerasomboon et al., 2022; Soga, Yamaguchi, et al., 2023). iEMG lacks this granularity, averaging the activation over time, and masking the critical changes in muscle activity at different angles (Ripley et al., 2024).

While EMG is useful for overall activity measurement, it does not capture the nuanced activation patters than occur at critical joint angles during the NHE, which provides less actionable information for refining exercise protocols. Therefore, it is proposed to measure EMG at both the BTA and the angle at peak EMG during the NHE, to provide complementary insights (Ripley et al., 2024; Šarabon et al., 2019). The BTA is associated with the maximum eccentric load that the knee flexors can sustain. Measuring EMG at the BTA will provide insight into how the BF_{LH} and ST behave under high-torque, lengthened conditions, which mimic injury-prone scenarios like the late swing phase of sprinting (Chumanov et al., 2012; Hirose et al., 2021; Schuermans et al., 2014). By analysing EMG at BTA, it can be determined if the BF_{LH} and ST are under-activated or compensating inadequately, important in rehabilitation (Schuermans et al., 2014). The angle at peak EMG is the angle at which the maximum EMG activity is recorded, indicating the highest neuromuscular activation during the exercise, providing valuable information about the muscle's recruitment patterns (Ripley et al., 2024). Identifying the peak activation angle of the knee flexors provides insight for optimising training protocols, as it allows practitioners to target specific ranges of motion where muscle force production and activation are maximised (Bourne et al., 2016; Opar, Williams, Timmins, et al., 2013). The angle of peak EMG allows for comparisons between the conventional and modified NHE variations, enabling assessment of how the incline set-up influences muscle activation patterns (Hirose et al., 2021; Šarabon et al., 2019).

Measuring EMG at both BTA and peak activation provides a complementary view of hamstring function. While BTA reflects mechanical failure under load and the limits of torque generation at specific joint angles, peak EMG highlights neuromuscular performance and the efficiency of muscle recruitment (Ripley et al., 2024; Sconce et al., 2021b; Soga et al., 2021). Together, they provide insight into both strength-length limits and activation efficiency (Ripley et al., 2024). Dual measurement can help identify specific deficiencies. For example, a participant displaying a small BTA with high EMG at earlier knee angles may have insufficient eccentric strength in lengthened positions. This is particularly relevant as HSIs frequently occur during eccentric loading at long muscle lengths (Guex et al., 2016; Tyler et al., 2017). By evaluating activation patterns at both BTA and peak EMG angles, practitioners can design targeted interventions to improve resilience in these critical positions (Hirose et al., 2021; Ripley et al., 2024; Schuermans et al., 2014; Van Dyk et al., 2019).

7.5 Standardising exercise technique during testing

Various NHE techniques have been reported in the literature, showing that it is a challenge to standardise results, protocols and technique across different studies (Alt et al., 2022; Sconce et al., 2021a). NHE hip flexion angle and the speed of the descent during the exercise will impact the resulting torque and BTA. Excessive hip flexion, as observed in razor curls, produces larger NHE torque values at the same knee angle compared to a neutral hip position (Pollard et al., 2019) potentially leading to different muscular adaptations due to operating at different muscle lengths (Baumgart et al., 2021; Bourne, Williams, et al., 2017; Kellis & Blazevich, 2022). Alt and Schmidt, (2021) state that poor execution of the NHE may impede or even prevent adaptations at long hamstring muscle lengths occurring at extended knee angles, which is important for eliciting the preventative adaptations required for HSI reduction. Sconce et al., (2024) implemented a visual software feedback system to monitor hip position and knee extension speed during the NHE, utilising an on-screen mannequin representation of a person and a pre-determined reference line to provide visual cues for the user. It was reported that compared to verbal feedback, the software feedback significantly decreased the mean of both the RTA by 5.7° ($d=0.514$, $p<0.01$) and the AVK by 8.7deg$\cdot$s^{-1}. Consequently, it is recommended to use this feedback system from **Chapter 6** to regulate exercise technique during the testing to promote standardised results across individuals.

7.6 Research design

The study employed a cross-sectional design, with all tests conducted within a single session for each participant. Each participant performed 3 repetitions of the conventional NHE and 3 repetitions of the 10° incline NHE. To minimise order effects, the sequence of flat and incline variations was alternated between participants.

7.6.1 Participants

Twenty-one recreationally active participants (n=21) of varying NHE training experience, gender, and age were recruited to participate in this study (Mean ± SD age 29 + 14years, height 171 ± 10.0cm, and body mass 68.3 ± 13.9kg). A sample size of 27 participants was determined a priori to achieve 80% statistical power with an alpha error probability of 0.05 and an effect size of 0.5. The choice of a moderate effect size (Cohen's d=0.5) was based on previous research reporting comparable magnitude of difference in hamstring activation and torque across NHE variations and feedback conditions (Keerasomboon et al., 2022; Ripley et al., 2024; Šarabon et al., 2019; Soga et al., 2021). Given that the incline NHE modifies the torque-length relationship and increases the proxy muscle length at peak torque (as shown in **Chapter 4**), a moderate change in BF_{LH} activation was anticipated. This assumption ensured sufficient sensitivity to detect practically meaningful but not extreme differences between the flat and incline conditions. Although the final sample comprised 21 participants, this is comparable with other NHE crossover design studies, such as those by Krommes et al., (2021), Jorge et al., (2024), and Walsh, O'Brien and Browne, (2024) where participant numbers ranged from 8–23. Moreover, in a similar study by Šarabon et al., (2019) which investigated variations of the NHE evaluating EMG, torque and 2D kinematic measures, a minimal sample size of 15 participants was calculated for 80% statistical power with an alpha error probability of 0.05. The study projected a required minimal sample of 15 but included 18. Furthermore, Ripley et al., (2024) had 13 participants performing NHE variations at three different slopes to examine the kinematic, neuromuscular and in-vivo mechanics of the BF_{LH} during the NHE.

Participants were eligible for study inclusion if they had experience of regular participation in lower limb strength training. Eligibility also required participants to be free from lower extremity injuries occurring within the past 6 months, and to have no history of recurrent injuries affecting the low-back, hip, thigh or knee. Recurrent injuries were defined as multiple episodes that either restricted physical activity or caused pain during exercise for more than 2 consecutive weeks on at least 2 or more occasions in the past 6 months. Exclusion criteria included any medical or health conditions that would contraindicate or impede performing maximal NHE testing. Ethical approval for the study was approved by the Sheffield Hallam University Ethics Committee (ER58577692).

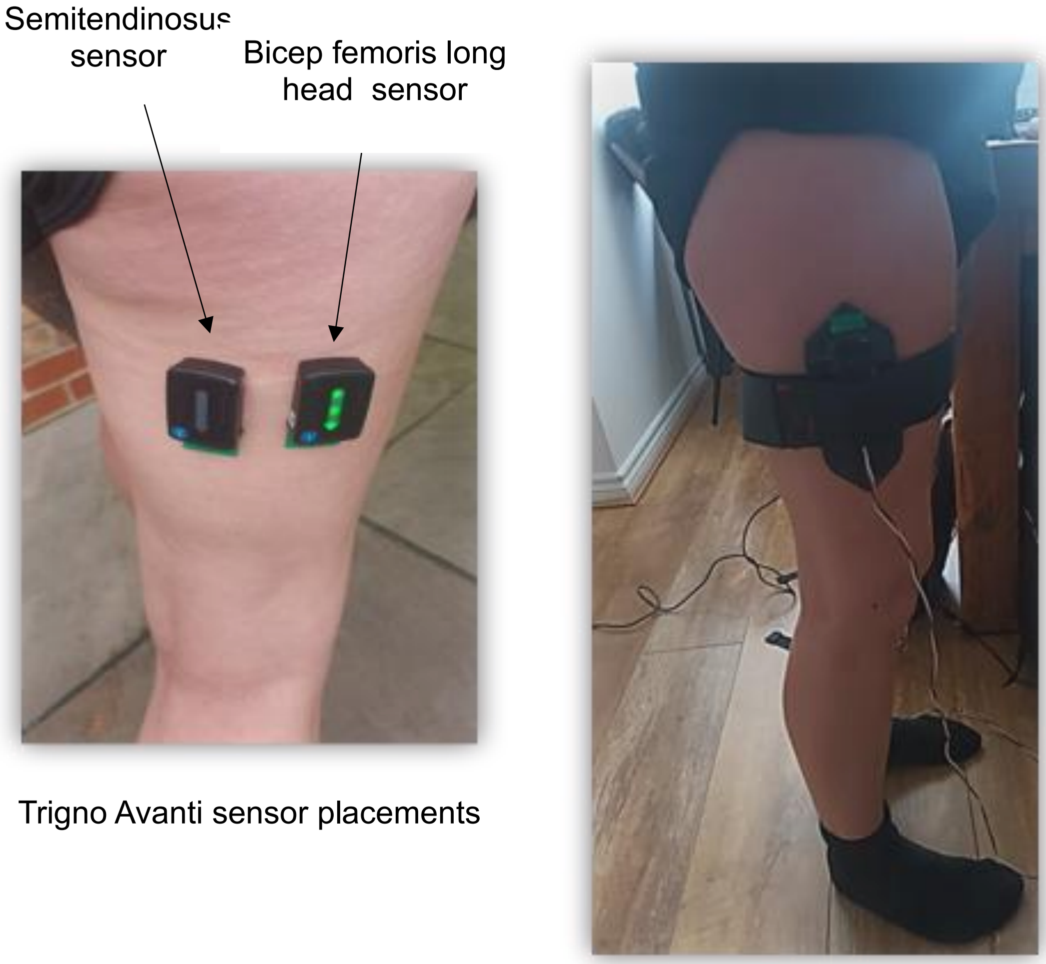
Prior to the NHE maximal testing, all participants underwent a standard 5-minute warm-up, which included dynamic stretching and a series of mobility and activation exercises. These purposefully targeted the lower body, with particular focus on the hamstrings, quadriceps and hip flexors (examples being bodyweight lunges, banded squats and walks, clams and glute bridges) to increase muscle temperature and heart rate. The warm-up protocol aimed to optimise performance and minimise risk of injury during testing. With respect to NHE familiarity, participants experience varied from no prior exposure (n=2) to limited experience through team warm-ups or rehabilitation settings (n=11), to regular use as a part of a structured strength training (n=8). All participants, regardless of prior experience, received a researcher visual demonstration of the NHE on the HALHAM° to ensure correct technique for protocol adherence. This was then followed by 3 sub-maximal practice attempts by the participant. There was a number of participants who had prior experience with the integrated biofeedback system (n=14). The remaining participants (n=7) received on-the-day biofeedback familiarisation training following the on-screen mannequin while performing the sub-maximal NHEs.

7.6.2 EMG method

sEMG activity of the BF_{LH}, and ST muscles was measured for all trials using the Trigno Wireless EMG system by Delsys Incorporated (Natick, MA, USA). Normalisation to a perceived maximum value was deemed unnecessary for this study, as comparisons of sEMG activity were to be made within individuals (i.e. between flat and incline NHE variations) rather than between individuals or groups. A standardised protocol was used to prepare the participants’ skin prior to electrode placement. This involved shaving the skin over the muscle sites with a disposable razor to remove any hair if necessary and then rubbing the skin with a preparation gel to remove dead skin cells and oil. The skin was then cleaned with a water-based solution to further reduce skin impedance and remove any remaining residues, whilst helping to maintain hydration. Skin preparation was performed to minimise resistance, aiming to reduce inter-electrode resistance to improve signal quality, enhance electrode contact and ensure consistency of measurement across participants.

Trigno Avanti sensors (measuring 27x37x13mm and weighing 14g) were placed on the surface of the skin of the right limb for each participant, aligning with the IMU placement on the HA*L*HAM° system (**Figure 38**). The same leg was used to maintain consistency in data collection and ensure accurate synchronisation between the two systems. Each sensor was securely attached using stickers specifically designed for the Avanti sensors. The placement was performed ensuring that no residue blocked the reference pad, which could interfere with the quality of the raw data. For the BF_{LH} and ST muscles, the sensors were positioned parallel to the orientation of each muscle’s fibres, which run longitudinally along the posterior thigh. For the BF_{LH}, the electrode was placed at the midpoint identified between the ischial tuberosity and lateral epicondyle. For the ST, the electrode was placed at the midpoint between the ischial tuberosity and the medial epicondyle (Watanabe et al., 2016). The quality of the sEMG signal was verified prior to the first maximal trial by visually inspecting the raw data for noise, defined as any non-physiological electrical activity, including baseline drift, high-frequency interference, or motion artefacts. Ensuring minimal noise and optimal signal integrity is needed for accurate representation of muscle activation patterns, particularly for dynamic movements such as the NHE (De Luca, 1997). Delsys Trigno® software was used to collect sEMG data from two sensors sampled at 1259.26Hz, providing sufficient resolution to capture rapid and transient fluctuations in muscle activity (Clancy et al., 2002). Concurrently, the IMU device recorded movement data at a sampling rate of 41.67Hz, which was suitable for capturing the lower frequency dynamic movement patterns while maintaining a manageable data set (Muro-de-la-Herran et al., 2014).

The wireless sEMG sensors transmitted real-time data to a Trigno Base receiver connected to a laptop running EMGworks® analysis software (Delsys Incorporated, Natick, MA, USA). Common methods of sEMG processing include filtering, normalisation and windowing (Fang et al., 2020). Within EMGworks® analysis, signal processing techniques and filtering were applied to the raw sEMG data to prepare it for further analysis. A root mean square (RMS) filter was used, employing a moving window of 125ms with a 62.5ms overlap. This filter calculated the square root of the mean squared signal within each window to produce a smoother representation of the EMG signal. The EMG data were further filtered using a custom MATLAB script (MathWorks, Inc., Natick, MA) to remove any unwanted, high-frequency noise while preserving the primary signal characteristics. A low-pass zero-phase shift Butterworth filter of order 2 with a cutoff frequency set to 5% of the Nyquist frequency was applied. This filter removed frequencies above approximately 1.05Hz, retaining slower signal components such as the main muscle activation patterns and filtering out high-frequency noise (electrical interference). EMG and EMG-angular metrics were subsequently calculated using a further custom MATLAB script (MathWorks, Inc., Natick, MA).



IMU sensor placement

Figure 38: Panel (A) shows the placement of the Trigno Avanti EMG sensors over the bicep femoris long head and semitendinosus muscles. Panel (B) illustrates the placement of the IMU sensor on its plastic carrier. A flexible wrap was used to secure the carrier around the thigh, which was then wrapped over the EMG sensors for enable stable positioning during testing.

7.6.3 HALHAM method and synchronisation

The thigh and trunk IMU sensors were positioned as described in **Chapter 6**, following the same standardised placement method to ensure consistency across trials. The positioning of the EMG sensors served as a useful reference for aligning the IMU holder, with the carrier straps securing both the IMUs and EMG electrodes to maintain stability and minimise noise during testing. To allow data synchronisation between the HA*L*HAM° and Trigno EMG system, a reference electrode was secured on to the HA*L*HAM° IMU carrier and configured to only collect IMU data. The thigh IMU was manually tapped simultaneously with the EMG reference sensor, enabling accurate temporal alignment of the datasets during subsequent data processing. The IMU device recorded data at a sampling rate of 41.67Hz, and the EMG reference sensor sampled at a rate of 370.37Hz. The offsets identified during this synchronisation were then applied in the MATLAB script to align the datasets. This synchronisation method has been demonstrated to provide high temporal reliability between IMU and EMG systems. Previous studies have shown that manual tapping of IMUs, and EMG reference electrodes produces consistent alignment of signals across trials, with intraclass correlation coefficients $\geq$0.95 for timing offsets (Camomilla et al., 2018). By applying the identified offsets, the HA*L*HAM° and sEMG system were aligned, ensuring that identical moments in time were captured across devices, thereby enabling valid comparisons between muscle activation and joint kinematics.

7.6.4 Nordic hamstring exercise trials

Each participant was asked to complete 3 maximal repetitions of the conventional flat NHE and 3 maximal repetitions of the incline NHE. The rest period between repetitions was long enough to allow the participant to recover for the next maximal effort ($\geq$ 6 secs) (Alt et al., 2021). In **Chapter 4**, participants rested for 15 minutes between feedback types to ensure full recovery. In the current study, the rest period between inclinations was adjusted to $\geq$ 6 minutes according to the most recent NHE evidence, and consistent with the recommendations of Alt et al., 2022). This approach ensured participants were adequately rested while reflecting current best practice for repeated NHE maximal contractions. Participants' NHE starting position was determined by lining up the lateral femoral epicondyle of the femur with the pivot point before commencement (Sconce et al., 2021b). Participants were asked to hold the hands in line with the shoulders, palms facing forward and gradually lean forward whilst following the biofeedback system (**Chapter 6**) which was used to track angular velocity of the knee and hip flexion. Responding to previous user feedback a modification was introduced to offset the reference line from the start position to behind neutral, allowing users to adjust to the pace and facilitating a smoother commencement. To maintain the movement speed at 20deg·s^{-1} for the 90° range of motion, the time counter was adjusted to reflect a 10° offset. Furthermore, to better represent the natural physiological curvature of the spine, a more permissible range of 20° for hip flexion was incorporated into the system (Alt & Schmidt, 2021a).

7.6.5 Metrics

As outlined in **Chapter 6,** injury risk factors metrics (peak torque, BTA) and exercise technique metrics (RTA and AVK) were computed using a custom MATLAB script (MathWorks, Inc., Natick, MA). Additionally, the processed data from EMGworks® analysis was exported to MATLAB, where further calculations of EMG and EMG-angular metrics were performed using custom scripts. These additional metrics included:

EMG metrics:

- **Bicep femoris long head peak EMG (BF_{LH} peak EMG)** ~ The maximum EMG activity recorded in the BF_{LH} muscle during the NHE. This value represents the peak electrical activity generated by the muscle during the exercise and is measured in microvolts (µV). This metric has been shown to provide reliable estimates of peak muscle activation during eccentric actions. Test re-test reliability for surface EMG recordings of the BF_{LH} is generally high (ICC=0.70-0.95) when electrode placement and skin preparations are standardised, following SENIAM guidelines (Kellis & Katis, 2008; Kotila et al., 2011).
- **Semitendinosus peak EMG (ST peak EMG)** ~ The maximum EMG activity recorded in the ST muscle during the NHE. Surface EMG recordings of the ST have demonstrated moderate to excellent test-retest reliability in previous studies (reported ICCs 0.62-0.91), with reproducibility improving when standardised electrode placement and skin preparation protocols are applied (Firmino et al., 2024).
- **Lateral to medial hamstring ratio (L-M ratio)** ~ The ratio of the maximum EMG activity recorded in the lateral (BF_{LH}) to medial (ST) hamstring muscles during the NHE. This metric is used to assess the

balance of muscle activation between the two muscles. This metric demonstrates acceptable reproducibility in hamstring exercise studies, given that individual BF_{LH} and ST EMG signals have ICCs shown in the range 0.62-0.95 (Firmino et al., 2024; Kellis & Katis, 2008; Kotila et al., 2011).

EMG-angular metrics:

- **Bicep femoris long head peak EMG angle (BF_{LH} peak EMG angle)** ~ The angle of the exercise at which EMG activity is recorded in the BF_{LH} muscle during the NHE. This metric indicates the specific joint angle corresponding to peak muscle activation. Measured in degrees (°).
- **Semitendinosus peak EMG angle (ST peak EMG angle)** ~ The angle of the exercise at which EMG activity is recorded in the ST muscle during the NHE. Measured in degrees (°).
- **Bicep femoris long head EMG at break-torque angle (BTA BF_{LH} EMG)** ~ The EMG activity recorded in the BF_{LH} muscle at the break-torque angle. This value reflects the muscles electrical activity at the point where the hamstring torque is highest and then begins to fall. Measured in µV.
- **Semitendinosus peak EMG at break-torque angle (BTA ST EMG)** ~ The EMG activity recorded in the ST muscle at the break-torque angle. Measured in µV.

The EMG-angular metrics introduced in this chapter are proposed as novel indicators of hamstring assessment, aiming to capture coordination between muscle activation and joint position during the NHE. Their interpretation is supported by the validated accuracy of the IMU system used to determine joint angles, with IMU-based angular tracking demonstrating excellent agreement with a gold-standard Polhemus motion capture system ($r=0.99$, $p<0.0001$). Furthermore, **Chapter 3** established the BTA as a reliable and reproducible metric representing the joint angle at which eccentric failure occurs, with small CV across participants (0.4-5.0%) Indicating low trial-to-trial variability. Therefore, capturing BF_{LH} and ST EMG at BTA is considered a valid and repeatable approach for examining muscle activation at the point of maximal eccentric loading, providing insight into inter-muscular coordination during the NHE.

7.6.6 Statistical analyses

126 trials from 21 participants (n=21) were initially considered (63 trials for each feedback condition). Trial exclusion criteria included the absence of a clear peak in the force-time trace, an extended plateau phase, or the lack of a distinct torque drop-off. Four trials were discarded due to EMG recording issues (n=2) and where a discernible peak in the torque traces could not be identified (n=2) leaving 122 trials for analysis. Data from the HA*L*HAM° IMU's were treated in MATLAB R2020b software (MathWorks, Inc., Natick, MA) and the data was subsequently statistically processed in GraphPad Prism 8.43 (GraphPad Software Inc). Normality of data was confirmed using the Shapiro-Wilk test and visually confirmed by Quantile-Quantile plots. Data for each participant were averaged across their 3 trials per condition. Descriptive statistics for each metric per testing condition (n=21) were calculated and reported as **Table 14**. In addition to analysing mean differences, within-session variability (CV%) was calculated for all metrics to determine whether inclination influenced measurement consistency, and whether the use of feedback further improves within-participant reliability (**Table 15**). Outliers were identified using the ROUT method (Q=1%). The following data points were flagged and subsequently excluded from the final analyses and graphical outputs:

Peak torque - flat*: 1 outlier (participant 16)*

Peak torque - incline*: 1 outlier (participant 16)*

BLD - flat*: 2 outliers (participants 5 and 11)*

Paired-samples t-tests were then used to compare differences in each metric between inclination conditions (flat and incline). HA*L*HAM° metrics compared were peak eccentric knee flexor torque (Nm), BTA (°), BLD (%), RTA (°) at peak torque, and AVK (deg·s^{-1}) at peak torque. The validity of these metrics has been supported in preceding chapters, with peak torque and BTA identified as the most reliable and meaningful performance and injury-risk indicators (CV% <10%). These variables demonstrated low within-session variability and consistent responses across different testing conditions, indicating strong measurement reliability. In contrast secondary technique-related measures (RTA and AVK) showed higher variability (CV% up to 90%), reflecting their sensitivity to individual

NHE execution rather than poor device reliability. Their inclusion remains valid, as they provide complementary contextual information on exercise quality rather than direct performance outcomes. EMG metrics compared were BF_{LH} and ST peak EMG (µV), L-M ratio, BF_{LH} and ST peak EMG angles (°), and BTA BF_{LH} and ST EMG (µV). Effect sizes were calculated by Cohen d and interpreted as small ($d \geq 0.2$), moderate ($d \geq 0.5$), and large ($d \geq 0.8$) (J. Cohen, 2013). Statistical significance was set at $p<0.05$ for all analyses. Results were reported as test statistics in the following format: test statistic (df) = value, p = …, effect size = …).

7.7 Results

Descriptive statistics for each metric per testing condition are shown in **Table 14** and reported as mean ± standard deviation. The variability for each metric is reported as the minimum to maximum value range. **Table 15** reports the corresponding CV% for each metric per inclination condition. Performance and injury-risk metrics (peak torque, BTA, BLD) are shown in **Figure 39** whilst NHE technique metrics (AVK and RTA) are shown in **Figure 40**. EMG metrics (BF_{LH} peak EMG, ST peak EMG, L-M ratio) are shown in **Figure 41**, and EMG-angular metrics (BF_{LH} peak EMG angle, ST peak EMG angle, BTA BF_{LH} EMG, BTA ST EMG) are shown in **Figure 42** illustrating any significance between inclinations.

Table 14: Mean, standard deviation and range reported for each metric per testing condition (n=21).

	FLAT testing		**INCLINE testing**	
Metrics	Mean ± SD	Range (Min-Max)	Mean ± SD	Range (Min-Max)
Kinetics				
Peak torque (Nm)	70.1 ± 21.6	41.8 – 125.5	71.7 ± 21.3	40.0 – 124.8
Kinematics				
BLD (%)	3.7 ± 2.5	1.0 – 11.4	5.2 ± 4.2	0.4 - 16.5
BTA (°)	120.3 ± 10.7* *c*	95.3 - 144.5	132.8 ± 8.6* *c*	108.0 - 150.4
RTA (°) at peak-torque	12.3 ± 5.1	1.6 - 23.2	11.8 ± 6.3	0.6 - 25.0
AVK ($deg \cdot s^{-1}$) at peak-torque	14.7 ± 5.9	2.3 - 27.8	13.1 ± 5.5	4.1 - 26.8
EMG				
BF_{LH} peak EMG (μV)	143.1 ± 67.7*	37.3 - 290.4	152.3 ± 63.5*	53.9 - 302.94
ST peak EMG (μV)	214.43 ±86.4**a*	81.4 - 401.9	186.14 ±60.5**a*	93.8 - 319.3
L-M ratio	0.66 ± 0.2* *c*	0.41 - 0.95	0.81 ± 0.2* *c*	0.51 - 1.27
EMG-angular				
BF_{LH} peak EMG Angle (°)	114.8 ± 8.6* *c*	94.1 - 144.2	128.8 ± 9.2* *c*	108.0 - 150.0
ST peak EMG Angle (°)	115.3 ± 9.5* *c*	94.0 - 142.4	126.5 ± 7.5* *c*	106.7 - 137.8
BTA BF_{LH} EMG (μV)	124.2 ± 60.7* *a*	37.2 - 255.0	139.3 ± 61.9* *a*	53.8 - 281.8
BTA ST EMG (μV)	189.3 ± 79.0* *a*	74.8 - 397.0	165.4 ± 54.5* *a*	90.5 - 308.7

Nm, Newton-metre, %, percentage difference,°, degrees, $deg \cdot s^{-1}$, degrees per second, μV, microvolts, BLD Bilateral limb torque difference, BTA Break-torque angle, RTA Relative trunk-to-thigh angle, AVK Angular velocity of the knee, BF_{LH} Bicep femoris long head, EMG Electromyography, ST Semitendinosus. L-M ratio Lateral to medial hamstring ratio

*denotes a significant difference between flat and incline variations ($p<0.01$)

a denotes a small effect size, *b* denotes medium effect size, *c* denotes large effect size

Table 15: CV% calculated from the 3 raw trials per participant (n=21), per condition, then averaged across participants.

Metrics	FLAT testing CV%	INCLINE testing CV%
Kinetics		
Peak torque (Nm)	30.8	29.6
Kinematics		
BLD (%)	69.4	78.1
BTA (°)	8.6	6.3
RTA (°) at peak-torque	39.8	50.0
AVK (deg·s^{-1}) at peak-torque	32.5	31.4
EMG		
BF_{LH} peak EMG (μV)	48.2	42.7
ST peak EMG (μV)	40.3	32.6
L-M ratio	24.3	23.0
EMG-angular		
BF_{LH} peak EMG Angle (°)	6.8	7.5
ST peak EMG Angle (°)	7.8	6.2
BTA BF_{LH} EMG (μV)	49.8	45.0
BTA ST EMG (μV)	40.6	30.8

Nm, Newton-metre, %, percentage difference,°, degrees, deg·s^{-1}, degrees per second, μV, microvolts, BLD Bilateral limb torque difference, BTA Break-torque angle, RTA Relative trunk-to-thigh angle, AVK Angular velocity of the knee, BF_{LH} Bicep femoris long head, EMG Electromyography, ST Semitendinosus. L-M ratio Lateral to medial hamstring ratio

7.7.1 Performance and injury risk factor metrics

Changes in mean peak torque, BLD and BTA across inclination conditions are shown in **Table 14** and **Figure 39**, with corresponding CV% values presented in **Table 15**. Outlier screening identified one participant as an outlier for peak torque in both flat and incline conditions, resulting in a final sample of n=20 (df=19) for torque analyses. Two participants were removed for BLD in the flat condition, yielding a matched sample of n=19 (df=18) for BLD analyses. Inclination type had no significant effect on eccentric knee flexor peak torque, $t(19)=1.56$, $p=0.135$, $d=0.118$. CV% values for peak torque were similar across conditions (flat 30.8%, incline 29.6%), indicating high within-session variability. BLD was also unaffected by inclination type, $t(18)=1.70$, $p=0.106$, $d=0.390$, with high variability observed in both conditions (flat 69.4%, incline 78.1%). Altering inclination significantly affected BTA, $t(20)=10.24$, $p<0.0001$, $d=1.294$, with incline testing producing a mean increase of 12.5° compared to flat testing. BTA demonstrated low within-session variability relative to other measures (flat 8.6%, incline 6.3%).

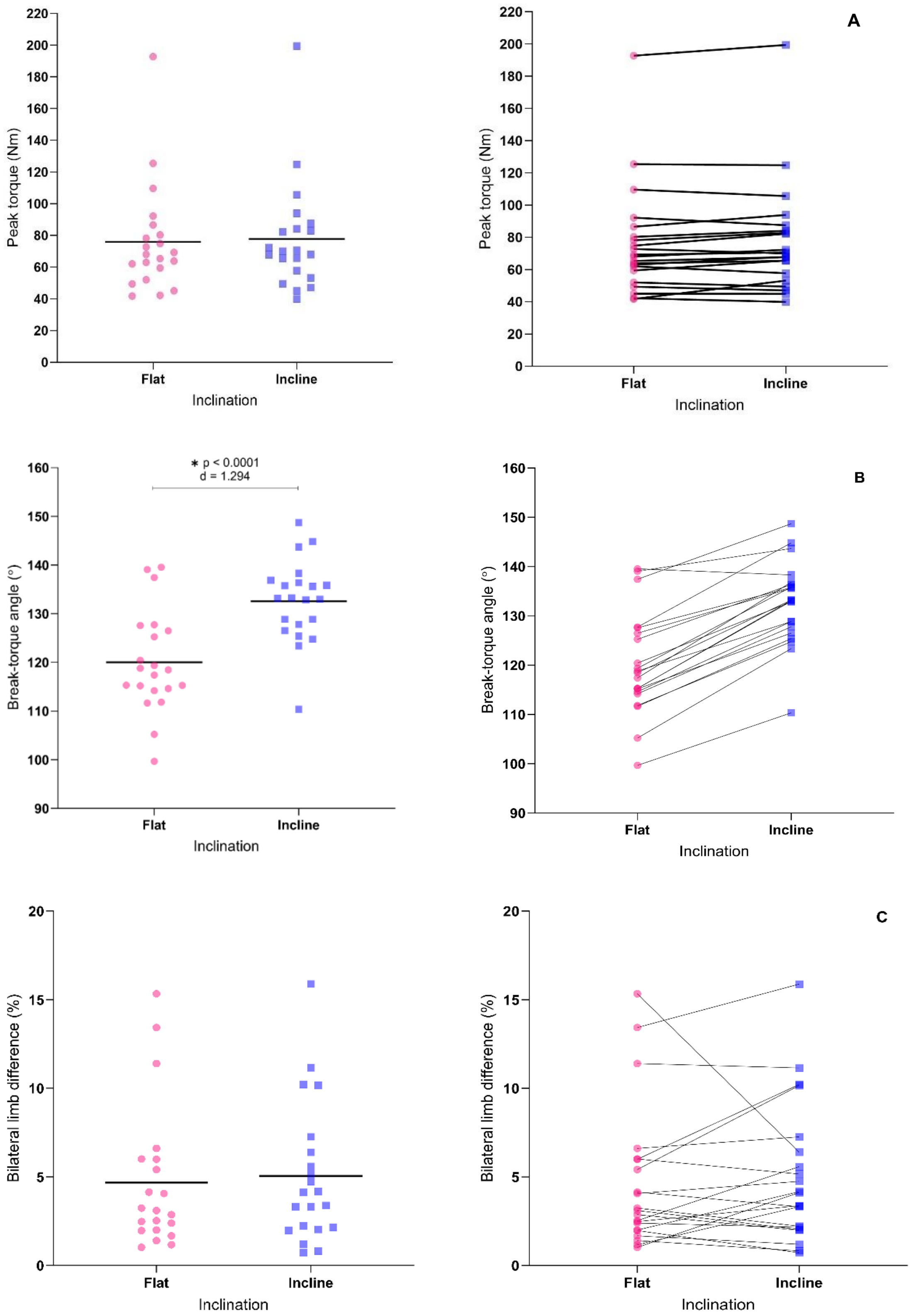


Figure 39: Eccentric knee flexor peak torque (A), break torque angle (B), and bilateral limb difference (C) for metrics for flat (n=61) and incline (n=61) conditions. Asterisks (*) indicate any significant differences between inclinations.

7.7.2 Exercise technique metrics

RTA and AVK changes with inclination can be seen in **Table 14** and **Figure 40**, with corresponding CV% values presented in **Table 15**. Altering inclination had no significant effect on RTA, t(20)=0.88, p=0.383, d=0.087 or AVK t(20)=1.59, p=0.127, d=0.281. Within-session variability for RTA remained high in both conditions, increasing from 39.8% (flat) to 50.0% (incline). AVK showed similar high variability, with CV% remaining comparable between conditions (3.2.5% flat vs. 31.4% incline).

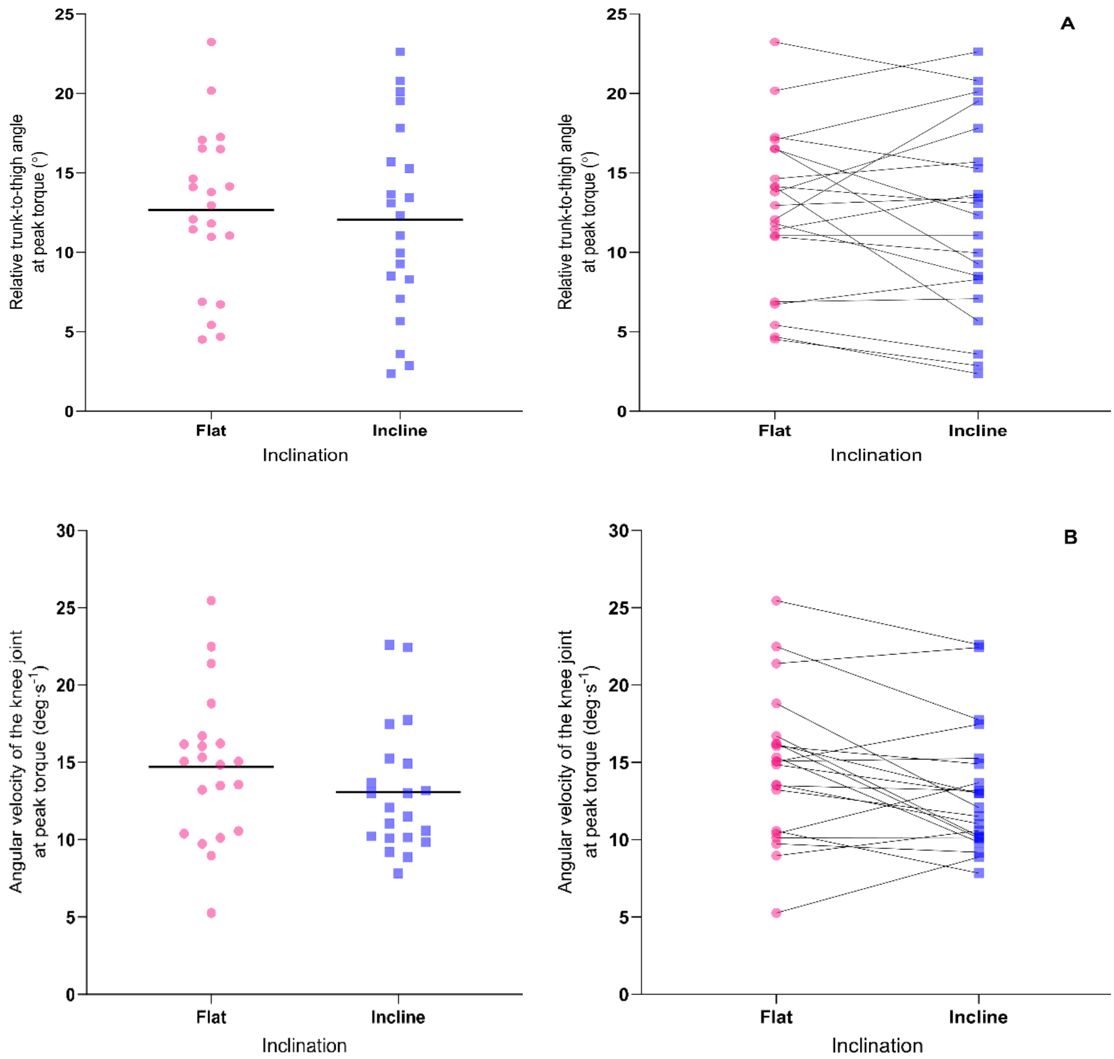


Figure 40: Relative trunk-to-thigh angle (A) and angular velocity of the knee joint (B) at peak torque technique metrics for flat (n=61) and incline (n=1) conditions. Asterisks (*) indicate any significant differences between inclinations.

7.7.3 EMG metrics

Changes in peak BF_{LH} EMG and peak ST EMG with inclination condition can be found in **Table 14** and **Figure 41**, with corresponding CV% values presented in **Table 15**. Inclination significantly affected peak BF_{LH} EMG, $t(20)=2.22$, $p<0.05$, $d=0.140$, showing a mean increase of 9.2μV when the NHE was performed on an incline compared to flat testing. However, the effect size was negligible indicating that the magnitude of the observed change may have limited practical significance. Inclination significantly affected peak ST EMG, $t(20)=3.74$, $p<0.01$, $d=0.379$, which lowered when the NHE was performed on an incline showing a mean decrease of 28.2μV compared to flat testing. The L-M ratio was significantly higher during incline testing, $t(20)=7.30$, $p<0.0001$, $d=0.750$, indicating a large effect of inclination on the relative activation of lateral (BF_{LH}) versus medial (ST) hamstring muscles. Within-session variability was high for BF_{LH} peak EMG (CV=48.2% flat, 42.7% incline) and ST peak EMG (CV=40.3=% flat, 32.6% incline), and lower for the L-M ratio (CV=20.3% flat, 23.0% incline).

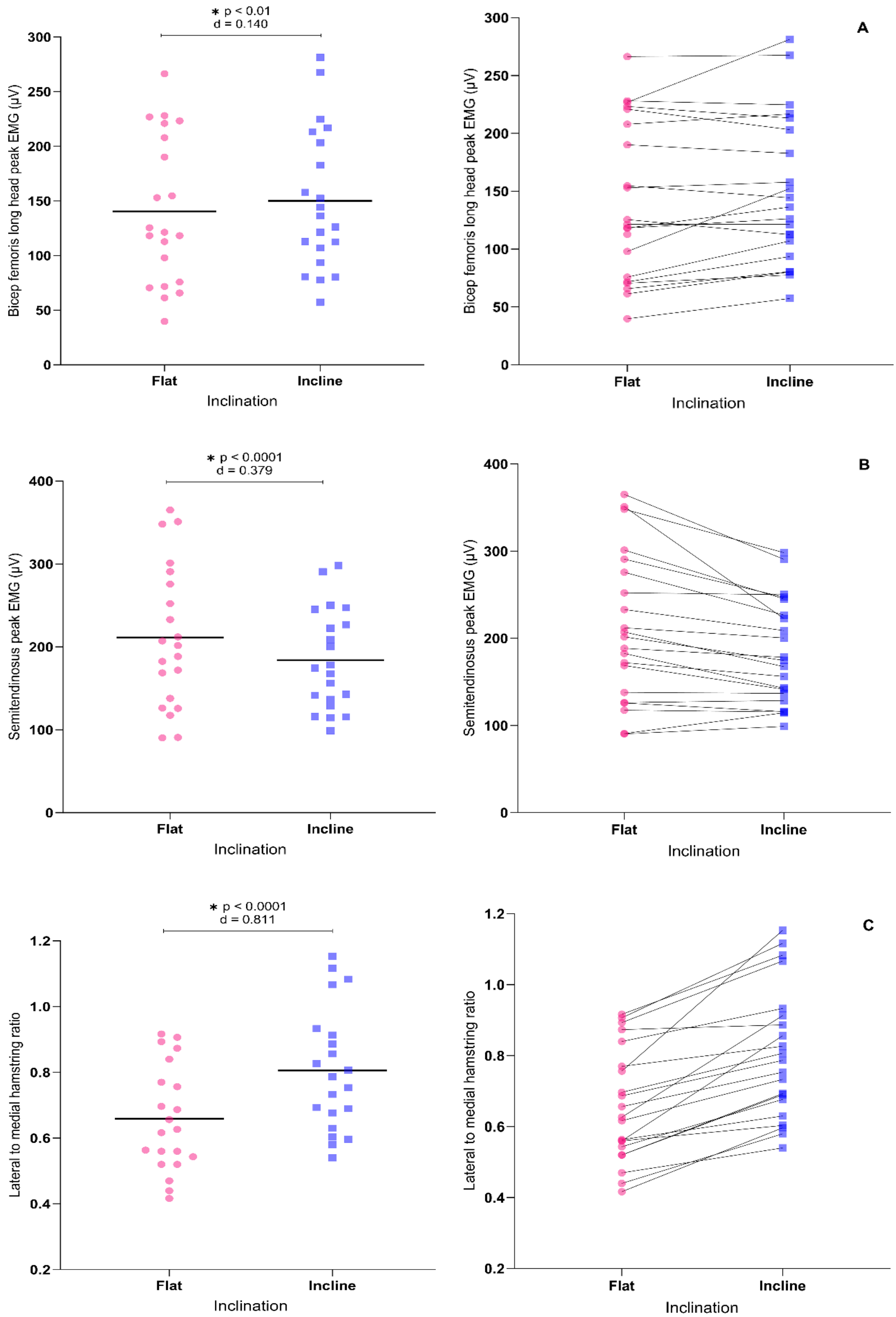


Figure 41: Peak bicep femoris long head electromyography (A), peak semitendinosus electromyography (B), and lateral-medial hamstring ratio (C) metrics for flat (n=61) and incline (n=61) conditions. Asterisks (*) indicate any significant differences between inclinations.

7.7.4 EMG-Angle metrics

Changes in BF_{LH} and ST peak EMG angles, and BTA BF_{LH} and ST EMG with inclination condition can be seen in **Table 14** and **Figure 42**, with corresponding CV% values presented in **Table 15**. Inclination significantly affected BF_{LH} peak EMG angle, $t(20)=9.74$, $p<0.0001$, $d=1.573$, which increased when the NHE was performed on an incline showing a mean increase of 14.0° compared to flat testing. Inclination significantly affected ST peak EMG angle, $t(20)=6.30$, $p<0.0001$, d=1. 309, which increased when the NHE was performed on an incline showing a mean increase of 11.2° compared to flat testing. Inclination significantly affected BF_{LH} EMG at BTA, $t(20)=2.77$, $p<0.05$, $d=0.246$, which increased when the NHE was performed on an incline showing a mean increase of 15.07μV compared to flat testing. Inclination significantly affected ST EMG at BTA, $t(20)=2.71$, $p<0.05$, $d=0.352$, which lowered when the NHE was performed on an incline showing a mean decrease of 23.9μV compared to flat testing. Within-session variability was low for BF_{LH} peak EMG angle (CV=6.8% flat, 7.5% incline) and ST peak EMG angle (CV=7.8% flat, 6.2% incline), and higher for BF_{LH} EMG at BTA (CV=49.8=% flat, 45.0% incline), and ST EMG at BTA (CV=40.6=% flat, 30.8% incline).

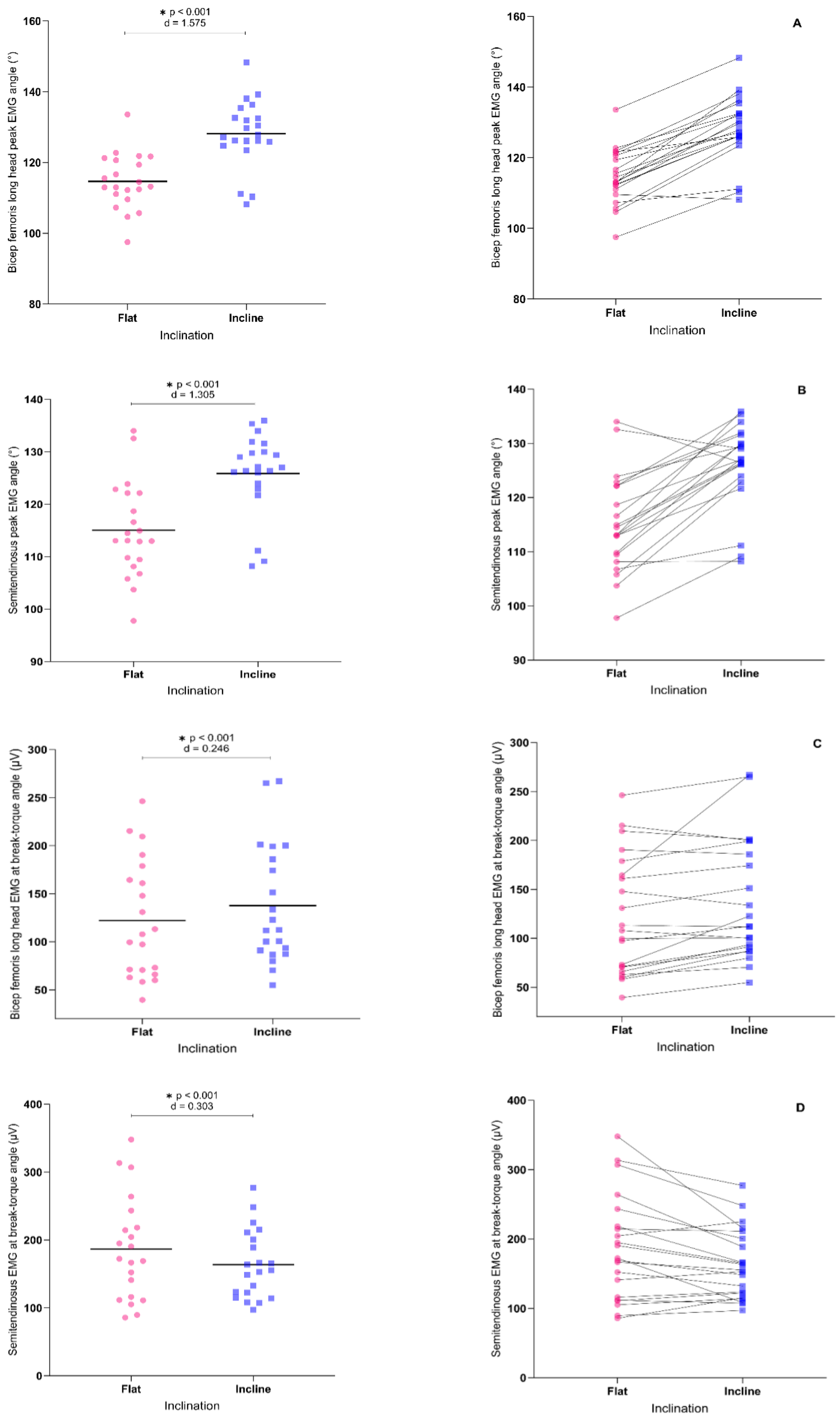


Figure 42: Bicep femoris long head peak electromyography angle (A), semitendinosus peak electromyography angle (B) EMG, break-torque angle bicep femoris long head peak electromyography (C), and break-torque angle semitendinosus peak electromyography (D) metrics for flat (n=61) and incline (n=61) conditions. Asterisks (*) indicate any significant differences between inclinations.

7.8 Discussion

Peak torque and normalised peak torque remained consistent between flat and incline conditions, demonstrating that altering the slope angle did not significantly influence maximal torque production during the NHE (**Table 14** and **Figure 39**). These findings confirm that both variations are equally effective in generating similar torque values, aligning with findings found in **Chapter 4** and Šarabon et al., (2019). In contrast, incline testing reported a significantly greater BTA, allowing the knee flexors to reach failure at more extended lengths. The magnitude of this change is likely meaningful, given that a 5-6° shift in BPA following NHE training is generally considered clinically significant (Delahunt et al., 2016). Such improvements are particularly relevant for targeting the proximal hamstrings, and hold implication for injury prevention and rehabilitation (Guex et al., 2016; Marušič et al., 2020; Tyler et al., 2017). Although torque measures showed high variability (CV~30%), the BTA demonstrated far lower variability, reinforcing confidence in the robustness of the angular findings.

Exercise technique was not significantly affected by slope condition, suggesting that incline testing does not alter the angular dynamics at peak torque. Hip flexion and descent speed at peak torque remained consistent across conditions, supporting previous findings from **Chapter 4** where RTA and AVK were unaffected by slope condition. Technique control in the present study was better than in earlier investigations (Chapters **3 and 4**), likely aided by familiarisation with the feedback system among two-thirds of the participants (n=14) who had prior experience of using it. Remaining participants (n=7) were familiarised on the day of testing, which likely also contributed to improved exercise consistency. Despite these improvements, technique-related metrics (RTA and AVK) still displayed high variability (CV ≈ 30-50%), suggesting that they are inherently less stable markers than angular or torque variables. However, the absence of a significant effect of inclination, combined with consistently high CV% values, indicate that technique-related metrics remain highly variable within and between individuals, and that differences observed across inclinations are likely driven by natural variation in NHE execution rather than any systematic influence of device reliability.

EMG findings demonstrated increased BF_{LH} peak activation and reduced peak ST activation under incline conditions, resulting in a higher L-M ration and suggesting a shift in activation favouring the BF_{LH}. Importantly, these changes occurred without reduction in torque output, implying that the incline modifies specific activation patterns rather altering load magnitude. CV values for EMG amplitudes were high (BF_{LH} 42-48%; ST 33-40%), which is expected for unnormalised sEMG during dynamic eccentric tasks, as absolute EMG amplitudes naturally differ across participants (Burden, 2010) and reflects electrode sensitivity, movement artefact, and the absence of a MVC (Balshaw et al., 2017; Burden, 2010; Farina et al., 2014). Despite this amplitude variability, the constant directional changes in BF_{LH} and ST activation across participants strengthen confidence in the interpretation of the EMG findings.

Both BF_{LH} and ST muscles reached peak activation at similar joint angles, suggesting shared contributions to controlling knee extension during the terminal eccentric phase (Soga, Hakariya, et al., 2023). However, the incline condition shifted these activation peaks to more extended positions, suggesting improved eccentric control close to terminal swing. When EMG activation was examined relative to the BTA, both muscles displayed peak activation slightly prior to mechanical failure, consistent with the protective eccentric braking mechanism (Chumanov et al., 2012; Kenneally-Dabrowski, Brown, et al., 2019; Ripley et al., 2024). At the break-point/failure, ST activity exceeded that of BF_{LH}, possibly reflecting its longer fascicle length and greater compliance, allowing it to tolerate rapid lengthening as BF_{LH} activation begins to decline (Higashihara et al., 2018; Soga, Hakariya, et al., 2023).

At the BTA, BF_{LH} EMG was significantly higher, and ST EMG was lower in the incline condition, indicating a functional shift toward lateral hamstring recruitment at extended muscle lengths. This pattern enhances the muscle’s ability to resist strain during long-length eccentric contractions, aligning with previous findings (Hirose et al., 2021; Keerasomboon et al., 2022; Soga, Hakariya, et al., 2023; Soga, Yamaguchi, et al., 2023). Variability For EMG at BTA remained high (CV ~ 30-50%) yet the consistent directional changes and alignment with torque and angular metrics suggest that incline condition reliably alters activation recruitment.

Peak BF_{LH} activation occurred at a significantly more extended angle in incline testing, closely mirroring the change observed in the BTA. This finding underscores the importance of assessing EMG activity in relation to angular data. Previous research similarly found close alignment between the NHE BPA and the angle of peak activation (Soga, Yamaguchi, et al., 2023). Peak ST activation also shifted toward extended angles, though to a lesser extent. These findings suggest that incline testing optimises activation length for both muscles but more prominently for $BF_{LH,}$ Research by Soga, Yamaguchi, et al., (2023) recommends intervention programmes that enhance BF_{LH} EMG activity at 145-165° of knee flexion. The incline condition notably contributes to achieving this target more effectively compared to the flat version.

Mechanistically, synthesising the torque, kinematic and EMG data suggests that incline testing shifts the torque-length relationship rightward by increasing muscle length and moment arm demands at equivalent torque levels. This promotes greater BF_{LH} engagement at long muscle lengths without compromising overall torque production. The concurrent reduction in ST activation indicates altered intramuscular load sharing, potentially reducing medial HSI risk. Collectively, the findings indicate that the incline NHE facilitates greater lateral hamstring engagement near terminal extension while maintaining torque, offering a practical strategy for BF_{LH} specific eccentric adaptation in both performance and p(rehabilitation) contexts.

7.9 Conclusion

The incline NHE can preferentially stimulate BF_{LH} activation at more extended muscle lengths in the proximal range, evidenced by the findings of increased peak EMG, greater break-torque angles and higher L-M ratios. Additionally, the reduction in ST activation during the incline NHE further promotes BF_{LH} recruitment while reducing potential overactivation of the medial hamstrings, offering significant benefits for both injury prevention and rehabilitation. Adding EMG-angular metrics to torque-angle assessment could more effectively support individualised NHE programming, providing a clearer understanding of the nuanced interplay between the BF_{LH}-ST muscles to promote a more favourable relationship between them at extended muscle lengths.

7.10 Chapter conclusion statement

To address the prevalence of HSIs in sports and overcome the limitations of current hamstring testing devices, a conceptualised biomechanical framework of the NHE was designed. From initial concept to final application, a novel device was developed to measure the torque-length dynamics of the knee flexors. The HA*L*HAM° is now a validated system capable of concurrently examining torque-angular relationships, kinetics, kinematics and muscle activation patterns during the NHE. It's integrated biofeedback functionality ensures standardised exercise technique, enhancing its utility in both research and practical applications. Angular measures have shown low variability, supporting their reliability for repeated assessment in combination with the already established torque profiling used by commercial hamstring testing and training devices. Exercise quality dependent metrics such as RTA and AVK continue to exhibit high within-session variability, although their CVs were reduced when biofeedback was used. To fully establish device reliability, particularly for technique metrics, repeated measures or longitudinal ICC based studies with sufficiently large trial volumes will be required.

Chapter 8

Synthesis of findings - HALHAM°: A Novel Device for Nordic Hamstring Exercise Assessment.

The overarching aim of this thesis was to design, validate and implement a novel hamstring assessment device capable of modifying and measuring the knee flexors' torque-length relationship across NHE inclinations, preferentially targeting the BF_{LH} at longer muscle lengths while maintaining torque production. This final chapter synthesises the findings from all preceding chapters, evaluating the extent to which each of the thesis objectives was achieved. It also provides a critical discussion of the strengths and limitations of the HALHAM° system and the research programme as a whole, before considering practical implications and directions for future research.

8.1 Chapter aim

The aim of this chapter is to synthesise the findings of the thesis and identify whether the overarching aims, themes and objectives have been met.

8.1.1 Chapter objectives

i. Synthesise findings from **Chapters 3-7**, evaluating the extent to which the overall thesis aims and objectives were achieved.

ii. Critically discuss the strengths, limitations, and contributions of the HA*L*HAM° system compared to existing hamstring devices.

iii. Outline the broader implications of the HA*L*HAM° system for hamstring testing, training and rehabilitation.

iv. Propose future research directions and practical applications.

8.2 Achievement of thesis objectives

The thesis objectives were set out under four main themes: Device development, standardisation, validation, and application:

8.2.2 Device development

The first theme objective was to design and develop a novel device capable of modifying and measuring the torque-length relationship of the knee flexors during the NHE. This was successfully achieved through the creation of the HA*L*HAM° device, which incorporates an adjustable angular mechanism, and allows concurrent measurement of angular-torque characteristics of the NHE by using an IMU-based system (**Chapter 2** and **Chapter 5**). Collectively, these features allow testing of the NHE across different inclinations and capture precise angle and torque data. The HA*L*HAM° system directly addressed limitations identified in **Chapter 1** concerning existing hamstring assessment devices, particularly their inability to measure the specific angle that torque can be produced, and that eccentric hamstring training at longer muscle lengths is desired.

A secondary objective was to incorporate a software-driven biofeedback system into the HA*L*HAM°. This was also achieved and using feedback was shown to reduce variability in technique metrics (AVK, RTA), improve standardisation and enhance measurement reproducibility (**Chapters 5** and **6**)

8.2.3 Standardisation

The second theme's objectives concerned establishing consistent NHE methods, terminology, and metrics for assessing both eccentric performance and exercise quality in the NHE. **Chapter 3** demonstrated that several commonly used metrics lacked agreement and measurement definition. Torque-angle metrics (BTA) demonstrated acceptable reliability reflected by low variability (CV <10%), which are the most critical indices for torque-length interpretation. Exercise quality metrics (AVK, RTA) showed high within-session variability (AVK at BTA, 3.5% to 63.8%; RTA at BTA; 8.3% to 96.5%) reflecting their sensitivity to individual exercise technique differences rather than poor measurement reliability. They were included in future studies to provide complementary information on exercise execution and inter-trial variability, helping to contextualise differences in performance outcomes. By introducing a unified framework of kinetic and kinematics, this thesis has provided suggested valid metrics that best reflect eccentric hamstring performance and technique control, that can support future NHE research and assessment.

8.2.4 Validation

The third theme's objectives were to determine the validity of the IMU-based HA*L*HAM° system against established gold-standard technologies. **Chapter 5** demonstrated that the HA*L*HAM° showed strong concurrent validity relative to the Polhemus system, evidenced by high correlations and narrow Bland-Altman limits of agreement ($r=0.99$, $p<0.0001$). These findings confirmed the accuracy of IMU integration while highlighting the added advantages of device portability and practical deployment.

8.2.5 Application

The final themes set of objectives related to applying the HA*L*HAM° system to investigate risk factors for HSI. **Chapter 4** showed that altering NHE inclination shifted the torque-length relationship rightwards, extending the peak torque production to longer muscle lengths i.e. larger BTA values, $F(2,34)=63.85$, $p<0.01$, $\omega^2=0.78$**.** **Chapter 7** showed that incline NHE testing preferentially activates peak BF_{LH} at longer muscle lengths, $t(20)=9.74$, $p<0.0001$, $d=1.573$ (+14.0°) compared to flat testing, targeting the most frequently injured HSI muscle at biomechanically relevant angles to HSI that occur in the late-swing phase.

Secondary objectives were to integrate a real-time software biofeedback system to monitor and guide NHE technique (**Chapters 5 and 6**). **Chapter 6** further demonstrated that software-based biofeedback improved exercise quality compared to verbal feedback, underlining its value in both research and applied contexts. RTA significantly decreased with feedback, $t(23)=2.98$ $p<0.01$, $d=0.51$, showing a mean decrease of 5.7°, compared to verbal instruction alone, and RTA variability reduced from 59.8% to 53.0% with feedback (compared to 92% in **Chapter 4**). AVK significantly decreased with feedback, $t(23)=3.67$, $p<0.01$, $d=0.825$, showing a mean decrease of 8.7 $deg \cdot s^{-1}$ compared to verbal instruction alone, and AVK variability reduced from 55.2% to 36.8% with feedback (compared with 65% in **Chapter 4**).

Taken together, the thesis objectives were largely achieved. The HA*L*HAM° system was successfully developed, validated and applied, producing new insights into NHE performance assessment and exercise quality feedback. The HA*L*HAM° system was able to measure and modify the torque-length relationship of the knee flexors', preferentially targeting the BLFH at longer muscle lengths, while maintaining torque production using the incline NHE. To understand where the device stands among existing hamstring devices, the comparison **Table 16** has been updated from **Table 1** in **Chapter 1**, and showcases the main current NHE testing and training devices available on the market now alongside the HA*L*HAM° model, highlighting the key features of each.

Table 16: Updated comparison table of the main existing hamstring devices.

Device	Manufacturer	Primary contraction mode	Kinetic measurement		Concurrent angle measurement	Adjustable inclination mechanism	Real-time kinetic feedback	Real-time feedback technique	Data logging software/ app	Portability	Price range
			Force	Torque							
Isokinetic Dynamometry	Various	Eccentric Isometric Concentric	✓	✓	*ROM (Not to measure BPA)*		✓		✓	Low	Varies between \$10000 - \$60000
Hand-held dynamometers	Various	Isometric	✓		*ROM*				*Some models have an app*	High	Varies between £100 - £2000
NordBord	Vald Performance	Eccentric	✓	*Approximated using knee position*			✓		✓	High	Approx \$5000 per year
Hamstring Solo	ND Sports Performance	Eccentric	✓	*Approximated using knee position*			✓		✓	High	Elite €5000 w/annual licensing fee of €2500
Hamtech	Human Kinematic	Assisted/Resisted Eccentric Isometric Concentric	✓	✓	*Hip and knee* ✓	*Hip angle can adjust*	✓		✓	Low	€20,000 - 30000

Ham’s Hell	WAW Athletik GmbH	Eccentric				Knee angle ✓				High	€3,749 – 3,948
KangaTech KT360	Kangatech	Eccentric Isometric	✓	✓					✓	High	*Not available*
H-RIG	H-RIG (Martin McIntyre)	Isometric	✓	✓					✓	Medium/ High	*Not available*
Nordic Hyper GHD	Freak Athlete Essentials LLC	Eccentric				Knee angle ✓				High	£599.99
HA*L*HAM°	SHU-SERG	Eccentric	✓	✓	✓	Knee angle ✓	*Available on screen but not directly used*	✓	Custom	Medium	n/a

8.3 Limitations of the thesis

Despite the advances reported in the thesis, several limitations must be acknowledged. Exercise quality metrics such as RTA and AVK continued to exhibit high within-session variability, although their CVs were reduced when biofeedback was implemented. To fully establish device reliability, particularly for assessing technique metrics, repeated measures or longitudinal ICC based studies with sufficiently large trial volumes will be required to capture true measurement stability.

Sample sizes across some studies were also modest, reducing statistical power and limiting generalisability. Additionally, while surface EMG provided important data on muscle activation it is inherently limited in distinguishing deep muscle activity and is susceptible to crosstalk. These limitations mean that conclusions regarding the specific role of the BF_{LH}, while suggestive should be interpreted cautiously.

While cross-sectional studies provided valuable insights, the absence of a longitudinal intervention meant that the long-term efficacy of incline NHE training could not be determined. Longitudinal studies using similar hamstring-strengthening NHE interventions (Arnason et al., 2008; Crawford et al., 2023; Cuthbert et al., 2020b; Presland et al., 2018; Siddle et al., 2018) have demonstrated improvements in hamstring strength, muscle activation and fascicle length, however further research is needed to confirm whether these outcomes extend to incline NHE training. It is reasonable to hypothesise that incline NHE training more effectively targets BF_{LH} EMG activity at longer muscle lengths, given that the cross-sectional study in **Chapter 7** reported a significantly greater mean NHE BTA of 12.5° for incline testing (132.8° vs. 120.3° for flat) and a significantly greater mean BF_{LH} peak EMG angle of 14.0° (128.8° vs. 114.8° for flat) for incline testing.

Several attempts were made to include an NHE training intervention study to examine the effect of incline training on muscle architecture and HSI risk factors. However, difficulties arose with participant recruitment, participant availability for the duration of the intervention, as well as logistical challenges related to the portability and setting up of the device in a suitable environment. These challenges were further exacerbated by the impact of COVID-19, which made potential student recruitment more difficult due to hybrid learning models, increased distance learning, and more students working to cover the cost-of-living affecting availability. Consequently, the feasibility of completing a comprehensive training intervention study under these conditions was significantly hindered. As a result, a more feasible cross-sectional study was conducted.

Other limitations of the research included challenges related to large scale recruitment and participant numbers, which added complexity to managing logistics at times. Additionally, being based away from the University campus in terms of locality, presented practical difficulties in coordinating testing sessions and ensuring consistent participant attendance. The portability of the complete HA*L*HAM° system also posed challenges, as its size and setup requirements limited its ease of transport and adaptability for off-campus research testing. These factors highlight areas of future development to enhance the accessibility and practicality of the system for broader research applications.

8.4 Implications

The findings of this thesis have several implications for both research and practice. First, the development of a device thar can modify the torque-length relationship offers researchers and practitioners a new means of assessing hamstring performance in positions more representative of injury-prone ranges. Second, the integration of biofeedback represents a step forward in standardising NHE technique and performance values, which have historically been difficult to monitor. Third, the identification of the incline NHE as a means of preferentially activating the BF_{LH} at longer muscles while maintaining torque production, provides a rationale for its use in rehabilitation and injury-prevention protocols.

8.5 User feedback improvements

User feedback throughout the process has resulted in several valuable design and software changes to the device, which have proven to be effective. Replacing the ankle straps with 3D printed hooks increased comfort and stability. The addition of a landing platform has counterbalanced weight distribution while providing a suitable area for free fall landings. The feedback system now features a reference guide figure that starts from a position behind neutral, allowing a 'preliminary movement phase' for users to adjust to the pace of the exercise before commencing.

8.6 Future research applications

Future work should focus on longitudinal training interventions to determine whether the acute benefits of incline NHE translate into meaningful adaptations in muscle architecture, strength, and injury risk reduction (Keerasomboon et al., 2022; Park et al., 2019; Schmitt et al., 2012; Soga et al., 2021; Tyler et al., 2017). Improving the portability and commercial viability of the HA*L*HAM° should also be prioritised, including the use of commercial-grade device materials, wireless IMU integration, Bluetooth connectivity for torque measurement, and enhanced software functionality such as gamification and benchmarking for personalised performance and technique feedback (Chalker et al., 2018; Phillips et al., 2013). In addition, the HA*L*HAM's adjustable range of ±20 at 5° increments, which was not explored in the present thesis, represents a promising avenue for future research, enabling the manipulation of eccentric (pre)rehabilitation protocols across a controlled spectrum of hip and knee angles (Marušič et al., 2020; Šarabon et al., 2019). Finally, larger multi-team and multi-sport studies could help establish normative databases, enabling personalised training and rehabilitation programmes, and allowing targeted interventions to reduce HSI risk (Ekstrand et al., 2022, 2023; Green et al., 2020; Hallén et al., 2024; Van Dyk et al., 2017, 2019).

8.7 Conclusions

The thesis has successfully developed, validated and applied the HA*L*HAM° system to investigate the torque-length relationship of the knee flexors during the NHE. By providing standardised methods and metrics, enabling incline variations that preferentially target the BF_{LH} at longer muscle lengths while maintaining torque production, and overcoming the key limitations of existing devices, the HA*L*HAM° system represents a significant advancement in hamstring assessment and NHE technique monitoring.

8.7.6 PhD reflections

The PhD journey has brought its challenges and rewards. Balancing part-time study with full-time employment and being a football coach has tested my resilience, time management and work-life balance. Navigating these responsibilities while pursuing academic goals has been demanding, but the experience has been profound. Throughout the journey I have acquired what I would consider invaluable skills. Organising numerous data collections, coordinating with lecturers, lab technicians, university staff, coaches, sports teams and students, and managing various aspects have of research have significantly enhanced my interactive and communication abilities. Additionally, I have learned to adapt to setbacks, such as dealing with device malfunctions, navigating the complexities of COVID-19 disruptions, and addressing challenges and disappointments with funding applications and journal rejections. Despite the obstacles, including periods of seemingly slow progress and the evolving landscape of similar research fields, I have been resilient and remained focused on the long-term goals, adapting and securing the novelty of the device developments, staying current with emerging research trends.

I have gained skills that a PhD experience typically provides, including advanced statistical analysis, data management, research design, technical equipment operation, proficiency in basic programming languages such as MATLAB, data visualisation, a strong understanding of ethical considerations, and effective research budget management. Moreover, I have developed wider skills that have equipped me with critical thinking. This has enabled me to evaluate findings, assess the validity and reliability of data, and challenge my own assumptions, whilst seeking opportunities and finding an inner adaptability to find solutions to problems. In addition, I have gained technical skills in areas such as ultrasound use and product design, which, while not directly applied in my research, have contributed to the depth of my experience. Opportunities to network, write and collaborate on funding proposals, present at a conference and produce a research poster for an inter-University competition have further enhanced my research experience.

An exciting aspect of the research has been exploring the commercial potential of the HA*L*HAM° device. Approaching and engaging with external companies has provided valuable experience in collaboration, potentially paving the way for real-world practical applications. The device has become a staple of the Universities engineering department and will hopefully be a valuable resource for future researchers and students working on hamstring injury projects. Completion of the PhD has laid a solid foundation for my future career development, whilst equipping me with the capability to contribute to various fields beyond academia and having the confidence to navigate life’s obstacles with resilience.

References

Ahmad, C. S., Redler, L. H., Ciccotti, M. G., Maffulli, N., Longo, U. G., & Bradley, J. (2013). Evaluation and management of hamstring injuries. *American Journal of Sports Medicine*, *41*(12), 2933–2947. https://doi.org/10.1177/0363546513487063

Al-Ayyad, M., Owida, H. A., De Fazio, R., Al-Naami, B., & Visconti, P. (2023). Electromyography monitoring systems in rehabilitation: a review of clinical applications, wearable devices and signal acquisition methodologies. In *Electronics (Switzerland)* (Vol. 12, Issue 7). MDPI. https://doi.org/10.3390/electronics12071520

Alegre, P., & Wales, N. S. (2021). Progressive workload periodization maximizes effects of Nordic hamstring exercise on muscle injury risk facrtors. *Journal of Strength and Conditioning Research*, *35*(4), 1006–1013.

Alonso-Fernandez, D., Docampo-Blanco, P., & Martinez-Fernandez, J. (2018). Changes in muscle architecture of biceps femoris induced by eccentric strength training with Nordic hamstring exercise. *Scandinavian Journal of Medicine and Science in Sports*, *28*(1), 88–94. https://doi.org/10.1111/sms.12877

Alt, T., Knicker, A. J., Nodler, Y. T., & Strüder, H. K. (2021). Assisted or unassisted Nordic hamstring exercise? Resistance exercise determinants at a glance. *Sports Biomechanics*, 1–15. https://doi.org/10.1080/14763141.2021.1893376

Alt, T., Knicker, A. J., Nodler, Y. T., & Strüder, H. K. (2023). What are we aiming for in eccentric hamstring training: angle-specific control or supramaximal stimulus? *Journal of Sport Rehabilitation*, *32*(7), 782–289.

Alt, T., Nodler, Y. T., Severin, J., Knicker, A. J., & Strüder, H. K. (2018). Velocity specific and time-dependent adaptations following a standardized Nordic hamstring exercise training. *Scandinavian Journal of Medicine & Science in Sports*, *28*(1), 65–76. https://doi.org/10.1111/sms.12868

Alt, T., Nodler, Y. T., Severin, J., Knicker, A. J., & Strüder, H. K. (2020). Comment on: “The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses". *Sports Medicine*, *50*(1), 219–221. https://doi.org/10.1007/s40279-019-01244-0

Alt, T., & Schmidt, M. (2021a). The ANHEQ evaluation criteria: introducing reliable rating scales for assessing Nordic hamstring exercise quality. *Sports Medicine*, *7*(91), 1–7. https://doi.org/10.1186/s40798-021-00383-x

Alt, T., & Schmidt, M. (2021b). The ANHEQ evaluation criteria: introducing reliable rating scales for assessing Nordic hamstring exercise quality. *Sports Medicine*, *7*(91), 1–7. https://doi.org/10.1186/s40798-021-00383-x

Alt, T., Severin, J., & Schmidt, M. (2022). Quo vadis Nordic hamstring exercise-related research? A scoping review revealing the need for improved methodology and reporting. In *International Journal of Environmental Research and Public Health* (Vol. 19, Issue 18). MDPI. https://doi.org/10.3390/ijerph191811225

Altman, D. G., & Bland, J. M. (1995). Statistics notes: the normal distribution. *British Medical Journal*, *310*(6975). https://doi.org/10.1136/bmj.310.6975.298.

Amundsen, R., Møller, M., & Bahr, R. (2023). Performing Nordic hamstring strength testing with additional weight affects the maximal eccentric force measured: do not compare apples to oranges. *BMJ Open Sport & Exercise Medicine*, *9*, 1–6. https://doi.org/10.1136/bmjsem-2023-001699

Andrade, C. (2018). Internal, external, and ecological validity in research design, conduct, and evaluation. *Indian J Psychol Med*, *40*(5), 498–499. https://doi.org/10.4103/IJPSYM.IJPSYM_334_18

Andrews, M. H., Shield, A. J., Lichtwark, G. A., & Pincheira, P. A. (2025). Hamstring injury mechanisms and eccentric training-induced muscle adaptations: current insights and future directions. *Sports Medicine*. https://doi.org/10.1007/S40279-025-02291-6,

Arnason, A., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2008). Prevention of hamstring strains in elite soccer: an intervention study.

Scandinavian Journal of Medicine and Science in Sports, *18*(1), 40–48. https://doi.org/10.1111/j.1600-0838.2006.00634.x

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports*, *13*(4), 244–250. https://doi.org/10.1034/j.1600-0838.2003.00312.x

Askling, C., Tengvar, M., Saartok, T., & Thorstensson, A. (2007). Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. *American Journal of Sports Medicine*, *35*(2), 197–206. https://doi.org/10.1177/0363546506294679

Augustsson, J., Alt, T., & Andersson, H. (2023). Speed matters in Nordic hamstring exercise: higher peak knee flexor force during fast stretch-shortening variant compared to standard slow eccentric execution in elite athletes. *Sports*, *11*(130), 1–12. https://doi.org/10.3390/sports11070130

Ayman, A., Attalah, O., & Shaban, H. (2020). Smart system for recognizing daily human activities based on wrist IMU sensors. *2019 International Conference on Advances in the Emerging Computing Technologies, AECT 2019*, 1–6. https://doi.org/10.1109/AECT47998.2020.9194154

Bahr, R., Thorborg, K., & Ekstrand, J. (2015). Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams : the Nordic Hamstring survey. *British Journal of Sports Medicine*, *49*(22), 1466–1471. https://doi.org/10.1136/bjsports-2015-094826

Balsalobre, C. (2017). *Nordics iOS (version 4.0) [Mobile app]*.

Balsalobre-Fernández, C., Glaister, M., & Lockey, R. A. (2015). The validity and reliability of an iPhone app for measuring vertical jump performance. *Journal of Sports Sciences*, *33*(15), 1574–1579. https://doi.org/10.1080/02640414.2014.996184

Balshaw, T. G., Fry, A., Maden-Wilkinson, T. M., Kong, P. W., & Folland, J. P. (2017). Reliability of quadriceps surface electromyography measurements is improved by two vs. single site recordings. *European Journal of Applied Physiology*, *117*(6), 1085. https://doi.org/10.1007/S00421-017-3595-Z

Baumgart, C., Kurz, E., Freiwald, J., & Hoppe, M. W. (2021). Effects of hip flexion on knee extension and flexion isokinetic angle-specific torques and HQ-ratios. *Sports Medicine - Open*, *7*(41), 1–10. https://doi.org/10.1186/s40798-021-00330-w

Beato, M., Madsen, E. E., Clubb, J., Emmonds, S., & Krustrup, P. (2024). Monitoring readiness to train and perform in female football: current evidence and recommendations for practitioners. *International Journal of Sports Physiology and Performance*, 1–9. https://doi.org/10.1123/ijspp.2023-0405

Beltran, L., Ghazikhanian, V., Padron, M., & Beltran, J. (2012). The proximal hamstring muscle-tendon-bone unit: a review of the normal anatomy, biomechanics, and pathophysiology. *European Journal of Radiology*, *81*(12), 3772–3779. https://doi.org/10.1016/j.ejrad.2011.03.099

Bengtsson, H., Ekstrand, J., Waldén, M., & Hägglund, M. (2018). Muscle injury rate in professional football is higher in matches played within 5 days since the previous match: a 14-year prospective study with more than 130 000 match observations. *British Journal of Sports Medicine*, *52*(17), 1116–1122. https://doi.org/10.1136/bjsports-2016-097399

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D., & Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *Br J Sports Med*, *32*(4), 309–314. https://doi.org/10.1136/bjsm.32.4.309

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *8*(1), 307–310. https://pubmed.ncbi.nlm.nih.gov/2868172/

Blumberg, B., Cooper, D. R., & Schindler, P. S. (2005). *Business Research Methods.* Berkshire: McGrawHill Education.

Bohm, S., Mersmann, F., & Arampatzis, A. (2015). Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. *Sports Medicine Open Access*, *1*(7), 1–18. https://doi.org/10.1186/s40798-015-0009-9

Bourne, M. N., Bruder, A. M., Mentiplay, B. F., Carey, D. L., Patterson, B. E., & Crossley, K. M. (2019). Eccentric knee flexor weakness in elite female footballers 1-10 years following anterior cruciate ligament reconstruction. *Physical Therapy in Sport*, *37*, 144–149. https://doi.org/10.1016/j.ptsp.2019.03.010

Bourne, M. N., Duhig, S., Timmins, R., Williams, M., Opar, D., Al Najjar, A., Kerr, G., & Shield, A. (2017). Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *British Journal of Sports Medicine*, *51*(5), 469–477. https://doi.org/10.1136/bjsports-2016-096130

Bourne, M. N., Opar, D. A., Williams, M. D., Al Najjar, A., & Shield, A. J. (2016). Muscle activation patterns in the Nordic hamstring exercise: impact of prior strain injury. *Scandinavian Journal of Medicine and Science in Sports*, *26*(6), 666–674. https://doi.org/10.1111/sms.12494

Bourne, M. N., Opar, D. A., Williams, M. D., & Shield, A. J. (2015). Eccentric knee flexor strength and risk of hamstring injuries in rugby union. *American Journal of Sports Medicine*, *43*(11), 2663–2670. https://doi.org/10.1177/0363546515599633

Bourne, M. N., Williams, M., Opar, D., Najjar, A., Kerr, G., & Shield, A. (2017). Impact of exercise selection on hamstring muscle activation. *British Journal Sport Science*, *51*(13), 1021–1028. https://doi.org/10.1136/bjsports-2015-095739

Brazier, J., Antrobus, M., Stebbings, G. K., Day, S. H., Callus, P., Erskine, R. M., Bennett, M. A., Kilduff, L. P., & Williams, A. G. (2020). Anthropometric and physiological characteristics of elite male rugby athletes. *Journal of Strength and Conditioning Research*, *6*(34), 1790–1801. www.nsca.com

Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower extremity stiffness: considerations for testing, performance enhancement, and injury risk. *Journal of Strength and Conditioning Research*, *33*(4), 1156–1166. https://doi.org/10.1519/JSC.0000000000002283,

Brockett, C. L., Morgan, D. L., & Proske, U. W. E. (2001). Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise*, *33*(5), 783–790.

Brockett, C. L., Morgan, D. L., & Proske, U. W. E. (2004). Predicting hamstring injury in elite athletes. *Medicine and Science in Sports and Exercise*, *36*(3), 379–387. https://doi.org/10.1249/01.MSS.0000117165.75832.05

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American Journal of Sports Medicine*, *34*(8), 1297–1306. https://doi.org/10.1177/0363546505286022

Brughelli, M., & Cronin, J. (2007). Altering the length-tension relationship with eccentric exercise: Implications for performance and injury. *Sports Medicine*, *37*(9), 807–826. https://doi.org/10.2165/00007256-200737090-00004

Buchheit, M., Cholley, Y., Nagel, M., & Poulos, N. (2016). The effect of body mass on eccentric knee-flexor strength assessed with an instrumented Nordic hamstring device (NordBord) in football players. *International Journal of Sports Physiology and Performance*, *11*(6), 721–726. https://doi.org/10.1123/ijspp.2015-0513

Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25years of research. *Journal of Electromyography and Kinesiology*, *20*(6), 1023–1035. https://doi.org/10.1016/j.jelekin.2010.07.004

Camomilla, V., Bergamini, E., Fantozzi, S., & Vannozzi, G. (2018). Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: a systematic review. *Sensors*, *18*(3), 1–50. https://doi.org/10.3390/S18030873

Campanini, I., Disselhorst-Klug, C., Rymer, W. Z., & Merletti, R. (2020). Surface EMG in clinical assessment and neurorehabilitation: barriers limiting its use. *Frontiers in Neurology*, *11*. https://doi.org/10.3389/fneur.2020.00934

Carmichael, D. S., Hickey, J. T., Tofari, P. J., Bourne, M. N., Ward, M. R., & Timmins, R. G. (2022). Impact of an isometric or eccentric hip extension intervention on hamstring strength, architecture and morphology. *Medicine & Science in Sports & Exercise*, *August*. https://doi.org/10.1249/MSS.0000000000003012

Cescon, C., Tettamanti, A., Barbero, M., & Gatti, R. (2015). Finite helical axis for the analysis of joint kinematics: comparison of an electromagnetic and an optical motion capture system. *Archives of Physiotherapy*, *8*(5), 1–8. https://doi.org/10.1186/s40945-015-0008-7

Chalker, W. J., Shield, A. J., Opar, D. A., Rathbone, E. N., & Keogh, J. W. L. (2018). Effect of acute augmented feedback on between limb asymmetries and eccentric knee flexor strength during the Nordic hamstring exercise. *PeerJ*, *6*(E4972), 1–14. https://doi.org/10.7717/peerj.4972

Charness, G., Gneezy, U., & Kuhn, M. A. (2012). Experimental methods: Between-subject and within-subject design. *Journal of Economic Behavior & Organization*, *81*(1), 1–8. https://doi.org/10.1016/J.JEBO.2011.08.009

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K. (2023). Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: a systematic review. *Physician and Sports Medicine*, *51*(1), 1–19. https://doi.org/10.1080/00913847.2021.1992601

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2007). The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of Biomechanics*, *40*(16), 3555–3562. https://doi.org/10.1016/j.jbiomech.2007.05.026

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2011). Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Medicine and Science in Sports and Exercise*, *43*(3), 525–532. https://doi.org/10.1249/MSS.0b013e3181f23fe8

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine*, *46*(2), 90. https://doi.org/10.1136/bjsports-2011-090176

Clancy, E. A., Morin, E. L., & Merletti, R. (2002). Sampling, noise-reduction and amplitude estimation issues in surface electromyography. *Journal of Electromyography and Kinesiology*, *12*(1), 1–16. https://doi.org/10.1016/S1050-6411(01)00033-5

Claudino, J. G., Cardoso Filho, C. A., Bittencourt, N. F. N., Gonçalves, L. G., Couto, C. R., Quintão, R. C., Reis, G. F., de Oliveira Júnior, O., Amadio, A. C., Boullosa, D., & Serrão, J. C. (2021). Eccentric strength assessment of hamstring muscles with new technologies: a systematic review of current methods and clinical implications. *Sports Medicine - Open*, *7*(10), 1–15. https://doi.org/10.1186/s40798-021-00298-7

Cohen, D., Zhao, Bingnan., Okwera, Brian., Matthews, M. J., & Delextrat, Anne. (2015). Angle-specific eccentric hamstring fatigue after simulated soccer. *International Journal of Sports Physiology and Performance*, *10*(3), 325–331. https://doi.org/10.1123/ijspp.2014-0088

Cohen, J. (2013). *Statistical power analysis for the behavioural sciences*. Routledge: Taylor & Francis.

Comfort, P., Regan, A., Herrington, L., Thomas, C., McMahon, J., & Jones, P. (2017). Lack of effect of ankle position during the Nordic curl on muscle activity of the biceps femoris and medial gastrocnemius. *Journal of Sport Rehabilitation*, *26*(3), 202–207. https://doi.org/10.1123/jsr.2015-0130

Concon, V., Kobal, R., Carvalho, L., Crivoi do Carmo, E., Coimbra, D., & Barroso, R. (2025). The effect of real-time visual feedback and verbal encouragement on repetition velocity of squat, bench press and deadlift exercises in competitive powerlifters. *International Journal of Sports Science and Coaching*, *20*(1), 275–280. https://doi.org/10.1177/17479541241298189

Crawford, S. K., Hickey, J., Vlisides, J., Chambers, J. S., Mosiman, S. J., & Heiderscheit, B. C. (2023). The effects of hip vs. knee dominant hamstring exercise on biceps femoris morphology, strength, and sprint performance: a randomized intervention trial protocol. *BMC Sports Science, Medicine and Rehabilitation*, *15*(72), 1–12.

Croisier, J. L. (2004). Factors associated with recurrent hamstring injuries. *Sports Medicine*, *34*(10), 681–695. https://doi.org/10.2165/00007256-200434100-00005

Cross, K. M., Gurka, K. K., Saliba, S., Conaway, M., & Hertel, J. (2013). Comparison of hamstring strain injury rates between male and female intercollegiate soccer athletes. *American Journal of Sports Medicine*, *41*(4), 742–748. https://doi.org/10.1177/0363546513475342

Cuthbert, M., Ripley, N., McMahon, J. J., Evans, M., Haff, G. G., & Comfort, P. (2020a). Reply to: "Comment on: The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses". *Sports Medicine*, *50*(1), 223–225. https://doi.org/10.1007/s40279-019-01245-z

Cuthbert, M., Ripley, N., McMahon, J. J., Evans, M., Haff, G. G., & Comfort, P. (2020b). The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses. *Sports Medicine*, *50*(1), 83–99. https://doi.org/10.1007/s40279-019-01178-7

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*(2), 135–163. https://doi.org/10.1123/JAB.13.2.135

De Winter, J. C. F. (2013). Using the student's t-test with extremely small sample sizes. *Practical Assessment, Research, and Evaluation Practical Assessment*, *18*, 10. https://doi.org/10.7275/e4r6-dj05

Delahunt, E., McGroarty, M., De Vito, G., & Ditroilo, M. (2016). Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. *European Journal of Applied Physiology*, *116*(4), 663–672. https://doi.org/10.1007/s00421-015-3325-3

Ditroilo, M., De Vito, G., & Delahunt, E. (2013). Kinematic and electromyographic analysis of the Nordic hamstring exercise. *Journal of Electromyography and Kinesiology*, *23*(5), 1111–1118. https://doi.org/10.1016/j.jelekin.2013.05.008

Drouin, J. M., Valovich-McLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European Journal of Applied Physiology*, *91*(1), 22–29. https://doi.org/10.1007/S00421-003-0933-0

Duhig, A. S. J., Bourne, M. N., Robert, L., Williams, M. D., Minett, G. M., Llion, A., Timmins, R. G., Sims, C. K. E., & Anthony, J. (2019). Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *Journal of Science and Medicine in Sport*, *22*(7), 769–774. https://doi.org/10.1016/j.jsams.2019.01.010

Ekstrand, J. (2013). Keeping your top players on the pitch: The key to football medicine at a professional level. *British Journal of Sports Medicine*, *47*(12), 723–724. https://doi.org/10.1136/bjsports-2013-092771

Ekstrand, J., Askling, C., Magnusson, H., & Mithoefer, K. (2013). Return to play after thigh muscle injury in elite football players: Implementation and validation of the Munich muscle injury classification. *British Journal of Sports Medicine*, *47*(12), 769–774. https://doi.org/10.1136/bjsports-2012-092092

Ekstrand, J., Bengtsson, H., Walden, M., Davison, M., & Hagglund, M. (2022). Still poorly adopted in male professional football: but teams that used the Nordic hamstring exercise in team training had fewer hamstring injuries – a retrospective survey of 17 teams of the UEFA Elite Club Injury Study during the 2020 – 2021 season. *BMJ Open Sport & Exercise Medicine*, *3*(8), 1–8. https://doi.org/10.1136/bmjsem-2022-001368

Ekstrand, J., Bengtsson, H., Waldén, M., Davison, M., Khan, K. M., & Hägglund, M. (2023). Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. *British Journal of Sports Medicine*, *57*(5), 292–298. https://doi.org/10.1136/bjsports-2021-105407

Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *American Journal of Sports Medicine*, *39*(6), 1226–1232. https://doi.org/10.1177/0363546510395879

Ekstrand, J., Healy, J. C., Waldén, M., Lee, J. C., English, B., & Hägglund, M. (2012). Hamstring muscle injuries in professional football: The correlation of MRI findings with return to play. *British Journal of Sports Medicine*, *46*(2), 112–117. https://doi.org/10.1136/112bjsports-2011-090155

Ekstrand, J., Waldén, M., & Hägglund, M. (2004). A congested football calendar and the wellbeing of players: Correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performers during that World Cup. *British Journal of Sports Medicine*, *38*(4), 493–497. https://doi.org/10.1136/bjsm.2003.009134

Ekstrand, J., Waldén, M., & Hägglund, M. (2016). Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA Elite Club injury study. *British Journal of Sports Medicine*, *50*(12), 731–737. https://doi.org/10.1136/bjsports-2015-095359

Eliakim, E., Morgulev, E., Lidor, R., & Meckel, Y. (2020). Estimation of injury costs: Financial damage of English Premier League teams' underachievement due to injuries. *BMJ Open Sport and Exercise Medicine*, *6*(1). https://doi.org/10.1136/bmjsem-2019-000675

Erickson, L. N., & Sherry, M. A. (2017). Rehabilitation and return to sport after hamstring strain injury. *Journal of Sport and Health Science*, *6*(3), 262–270. https://doi.org/10.1016/j.jshs.2017.04.001

Fang, C., He, B., Wang, Y., Cao, J., & Gao, S. (2020). EMG-centered multisensory based technologies for pattern recognition in rehabilitation: state of the art and challenges. In *Biosensors* (Vol. 10, Issue 8). MDPI. https://doi.org/10.3390/BIOS10080085

Farina, D., Merletti, R., & Enoka, R. M. (2014). The extraction of neural strategies from the surface EMG: an update. *Journal of Applied Physiology (Bethesda,* *Md. : 1985)*, *117*(11), 1215–1230. https://doi.org/10.1152/JAPPLPHYSIOL.00162.2014

Feiring, D. C., Ellenbecker, T. S., & Derscheid, G. L. (1990). Test-retest reliability of the biodex isokinetic dynamometer. *The Journal of Orthopaedic and Sports Physical Therapy*, *11*(7), 298–300. https://doi.org/10.2519/JOSPT.1990.11.7.298

Firmino, T., Mendes, B., Oliveira, R., Vaz, J., Radaelli, R., & Freitas, S. (2024). Semitendinosus and biceps femoris long head activity during the single leg bridge test in healthy individuals. *Journal of Bodywork and Movement Therapies*, *39*, 435–440. https://doi.org/10.1016/j.jbmt.2024.03.033

Foreman, T. K., Addy, T., Baker, S., Burns, J., Hill, N., & Madden, T. (2006). Prospective studies into the causation of hamstring injuries in sport: A systematic review. *Physical Therapy in Sport*, *7*(2), 101–109. https://doi.org/10.1016/j.ptsp.2006.02.001

Fothergill, S. (2010). Examining the effect of real-time visual feedback on the quality of rowing technique. *Procedia Engineering*, *2*(2), 3083–3088. https://doi.org/10.1016/J.PROENG.2010.04.115

Franchi, M. V, Reeves, N. D., Narici, M. V, & Huey, K. (2017). Skeletal muscle remodeling in response to eccentric vs. concentric loading: Morphological, molecular, and metabolic adaptations. *Frontiers in Physiology*, *8*(July), 1–16. https://doi.org/10.3389/fphys.2017.00447

Freckleton, G., & Pizzari, T. (2013). *Risk factors for hamstring muscle strain injury in sport : a systematic review and meta-analysis*. 351–358. https://doi.org/10.1136/bjsports-2011-090664

Fuller, C. W., Taylor, A., Douglas, M., & Raftery, M. (2020). Rugby World Cup 2019 injury surveillance study. *South African Journal of Sports Medicine*, *32*(1), 2–7. https://doi.org/10.17159/2078-516X/2020/v32i1a8062

Fyfe, J. J., Opar, D. A., Williams, M. D., & Shield, A. J. (2013). The role of neuromuscular inhibition in hamstring strain injury recurrence. *Journal of Electromyography and Kinesiology*, *23*(3), 523–530. https://doi.org/10.1016/j.jelekin.2012.12.006

Gabbe, B. J., Bennell, K. L., Finch, C. F., Wajswelner, H., & Orchard, J. W. (2006). Predictors of hamstring injury at the elite level of Australian football. *Scandinavian Journal of Medicine and Science in Sports*, *16*(1), 7–13. https://doi.org/10.1111/j.1600-0838.2005.00441.x

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise mechanisms and recommendations for training practices. *Sports Medicine*, *36*(2), 133–149. https://doi.org/10.2165/00007256-200636020-00004

Giacomo, J., Lahti, J., Hegyi, A., Gerus, P., & Morin, J. (2018). A new testing and training device for hamstring muscle function. *Sport Performance & Science Reports*, *40*(1), 1–4.

Giavarina, D. (2015). Understanding bland altman analysis. *Biochemia Medica*, *25*(2), 141–151. https://doi.org/10.11613/BM.2015.015

Giraudeau, B., Caille, A., Eldridge, S. M., Weijer, C., Zwarenstein, M., & Taljaard, M. (2022). Heterogeneity in pragmatic randomised trials: sources and management. *BMC Medicine*, *20*(1), 1–16. https://doi.org/10.1186/S12916-022-02569-W/TABLES/13

Goldspink, G. (1985). Malleability of the motor system: A comparative approach. *The Journal of Experimental Biology*, *115*, 375–391.

Goode, A. P., Reiman, M. P., Harris, L., DeLisa, L., Kauffman, A., Beltramo, D., Poole, C., Ledbetter, L., & Taylor, A. B. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*(6), 349–356. https://doi.org/10.1136/bjsports-2014-093466

Grange, S., Reurink, G., Nguyen, A. Q., Riviera-Navarro, C., Foschia, C., Croisille, P., & Edouard, P. (2023). Location of hamstring injuries based on magnetic resonance imaging: A systematic review. In *Sports Health* (Vol. 15, Issue 1, pp. 111–123). SAGE Publications Inc. https://doi.org/10.1177/19417381211071010

Green, B., Bourne, M. N., Van Dyk, N., & Pizzari, T. (2020). Recalibrating the risk of hamstring strain injury (HSI) - A 2020 systematic review and meta-analysis of risk factors for index and recurrent HSI in sport. *British Journal of Sports Medicine*, *0*, 1–10. https://doi.org/10.1136/bjsports-2019-100983

Green, B., Bourne, M., & Pizzari, T. (2018). Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *52*(5), 329–336. https://doi.org/10.1136/bjsports-2017-098101

Grgic, J., Lazinica, B., Schoenfeld, B. J., & Pedisic, Z. (2020). Test-retest reliability of the one-repetition maximum (1RM) strength assessment: A systematic review. *Sports Med Open*, *31*(6), 1–16. https://doi.org/10.1186/s40798-020-00260-z

Guex, K., Degache, F., Morisod, C., Sailly, M., & Millet, G. P. (2016). Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training. *Frontiers in Physiology*, *7*(8), 1–9. https://doi.org/10.3389/fphys.2016.00340

Guex, K., Gojanovic, B., & Millet, G. P. (2012a). Influence of Hip-Flexion Angle on Hamstrings Isokinetic Activity in Sprinters. *Journal of Athletic Training*, *47*(4), 390–395. https://doi.org/10.4085/1062-6050-47.4.04

Guex, K., Gojanovic, B., & Millet, G. P. (2012b). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training*, *47*(4), 390–395. https://doi.org/10.4085/1062-6050-47.4.04

Guo, Y., Logan, H. L., Glueck, D. H., & Muller, K. E. (2013). Selecting a sample size for studies with repeated measures. *BMC Medical Research Methodology*, *13*, 100. https://doi.org/10.1186/1471-2288-13-100

Hägglund, M., Waldén, M., & Ekstrand, J. (2006). Previous injury as a risk factor for injury in elite football: A prospective study over two consecutive seasons. *British Journal of Sports Medicine*, *40*(9), 767–772. https://doi.org/10.1136/bjsm.2006.026609

Hallén, A., & Ekstrand, J. (2014). Return to play following muscle injuries in professional footballers. *Journal of Sports Sciences*, *32*(13), 1229–1236. https://doi.org/10.1080/02640414.2014.905695

Hallén, A., Tomás, R., Ekstrand, J., Bengtsson, H., Steen, E. Van Den, Hägglund, M., & Waldén, M. (2024). UEFA women's elite club injury study: a prospective study on 1527 injuries over four consecutive seasons 2018/2019 to 2021/2022 reveals thigh muscle injuries to be most common and ACL injuries most burdensome. *British Journal of Sports Medicine*, *0*, 1–9. https://doi.org/10.1136/bjsports-2023-107133

Hawkins, R. D. (2001). The association football medical research programme: an audit of injuries in professional football. *British Journal of Sports Medicine*, *35*(1), 43–47. https://doi.org/10.1136/bjsm.35.1.43

Hegyi, A., Lahti, J., Giacomo, J.-P., Gerus, P., Cronin, N. J., & Morin, J.-B. (2019). Impact of hip flexion angle on unilateral and bilateral Nordic hamstring exercise torque and high-density electromyography activity. *Journal of Orthopaedic & Sports Physical Therapy*, *49*(8), 584–592. https://doi.org/10.2519/jospt.2019.8801

Hegyi, A., Péter, A., Finni, T., & Cronin, N. J. (2018). Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography. *Scandinavian Journal of Medicine and Science in Sports*, *28*(3), 992–1000. https://doi.org/10.1111/sms.13016

Heiderscheit, B. C., Hoerth, D. M., Chumanov, E. S., Swanson, S. C., Thelen, B. J., & Thelen, D. G. (2005). Identifying the time of occurrence of a hamstring strain injury during treadmill running: A case study. *Clinical Biomechanics*, *20*(10), 1072–1078. https://doi.org/10.1016/j.clinbiomech.2005.07.005

Heiser, T. M., Weber, J., Sullivan, G., Clare, P., & Jacobs, R. R. (1984). Prophylaxis and management of hamstring muscle strains in intercollegiate football players. *American Journal of Sports Medicine*, *12*(5), 368–370.

Hencken, C., & White, C. (2006). Anthropometric assessment of Premiership soccer players in relation to playing position. *European Journal of Sport Science*, *6*(4), 205–211. https://doi.org/10.1080/17461390601012553

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2015). Gait and posture differences in activation properties of the hamstring muscles during overground sprinting. *Gait & Posture*, *42*(3), 360–364. https://doi.org/10.1016/j.gaitpost.2015.07.002

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2016). Relationship between the peak time of hamstring stretch and activation during sprinting. *European Journal of Sport Science*, *16*(1), 36–41. https://doi.org/10.1080/17461391.2014.973913

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2018). Differences in hamstring activation characteristics between the acceleration and maximum-speed phases of sprinting. *Journal of Sports Sciences*, *36*(12), 1313–1318. https://doi.org/10.1080/02640414.2017.1375548

Higashihara, A., Nagano, Y., & Takahashi, K. (2015). Effects of forward trunk lean on hamstring muscle kinematics during sprinting. *Journal of Sports Sciences*, *33*(13), 1366–1375. https://doi.org/10.1080/02640414.2014.990483

Hirose, N., Tsuruike, M., & Higashihara, A. (2021). Biceps femoris muscle is activated by performing Nordic hamstring exercise at a shallow knee flexion angle. *Journal of Sports Science and Medicine*, *20*(2), 275–283. https://doi.org/10.52082/jssm.2021.275

Hody, S., Croisier, J. L., Bury, T., Rogister, B., & Leprince, P. (2019). Eccentric muscle contractions: risks and benefits. *Frontiers in Physiology*, *10*, 1–18. https://doi.org/10.3389/fphys.2019.00536

Hopkins, W. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*(1), 1–15. https://doi.org/10.2165/00007256-200030050-00005

Hopper, D. M., Anders, M., Berg, A., Andersen, H., & Madan, R. (2003). The influence of visual feedback on power during leg press on elite women field hockey players. *Physical Therapy in Sport*, *4*(4), 182–186. https://doi.org/10.1016/S1466-853X(03)00068-3

Huang, X., Xue, Y., Ren, S., & Wang, F. (2023). Sensor-based wearable systems for monitoring human motion and posture: a review. *Sensors*, *23*(22), 9047. https://doi.org/10.3390/s23229047

Ichihashi, N., Itoh, H., Yoshida, M., Shinohara, H., & Taketomi, Y. (1992). Torque-velocity relationships during concentric and eccentric contractions of the quadriceps and hamstrings muscles. *Physical Therapy Japan*, *19*(4).

Iga, J., Fruer, C. S., Deighan, M., Croix, M. D. S., & James, D. V. B. (2012). Nordic hamstrings exercise - Engagement characteristics and training responses. *International Journal of Sports Medicine*, *33*(12), 1000–1004. https://doi.org/10.1055/s-0032-1304591

Impellizzeri, F. M., McCall, A., & van Smeden, M. (2021). Why methods matter in a meta-analysis: a reappraisal showed inconclusive injury preventive effect of Nordic hamstring exercise. *Journal of Clinical Epidemiology*. https://doi.org/10.1016/j.jclinepi.2021.09.007

Ishikawa, M., Niemelä, E., & Komi, P. V. (2005). Interaction between fascicle and tendinous tissues in short contact stretch-shortening cycle exercise with varying eccentric intensities. *Journal of Applied Physiology*, *99*(1), 217–223. https://doi.org/10.1152/japplphysiol.01352.2004.

Ishøi, L., Hölmich, P., Aagaard, P., Thorborg, K., Bandholm, T., & Serner, A. (2018). Effects of the Nordic Hamstring exercise on sprint capacity in male football players: a randomized controlled trial. *Journal of Sports Sciences*, *36*(14), 1663–1672. https://doi.org/10.1080/02640414.2017.1409609

Ishøi, L., Krommes, K., Husted, R. S., Juhl, C. B., & Thorborg, K. (2020). Diagnosis, prevention and treatment of common lower extremity muscle injuries in sport – grading the evidence: a statement paper commissioned by the Danish Society of Sports Physical Therapy (DSSF). *British Journal of Sports Medicine*, *9*(54), 1–12. https://doi.org/10.1136/bjsports-2019-101228

Ivan, Z. (2012). Anatomy, physiology and biomechanics of hamstrings injury in football and effective strength and flexibility exercises for its prevention. *Journal of Human Sport and Exercise*, *7*(1), 11–14. https://doi.org/10.4100/jhse.2012.7.Proc1.24

Jaric, S. (2015). Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *International Journal of Sports Medicine*, *36*(9), 699–704. https://doi.org/10.1055/S-0035-1547283

Jeffery, J. (2018). *Quantifying eccentric hamstring strength in elite academy footballers: analysis of the NordBord and IKD* (Issue September). University of Central Lancashire.

Jorge, A., Lichtenstein, E., Faude, O., & Roth, R. (2024). Muscle activity and kinematics during three hamstring strengthening exercises compared to sprinting: a cross-sectional study. *International Journal of Sports Physical Therapy*, *19*(5), 569–580. https://doi.org/10.26603/001c.116158

Joshua, D. J., Breen, D., Roe, G., Till, K., & Jones, B. (2021). Between-day reliability of the Hamstring Solo device during the Nordic hamstring curl. *Journal of Australian Strength and Conditioning*, *29*(2), 5–11.

Kalkhoven, J. T., & Watsford, M. L. (2020). Mechanical contributions to muscle injury: implications for athletic injury risk mitigation. *SportRxiv*, *15*, 1–17. https://doi.org/10.31236/osf.io/a5um4

Keerasomboon, T., Soga, T., & Hirose, N. (2022). Influence of altered knee angle on electromyographic activity of hamstring muscles between Nordic hamstring exercise and Nordic hamstring exercise with incline slope lower leg board. *International Journal of Sports Physical Therapy*, *17*(5), 832–840.

Keller, M., Lauber, B., Gehring, D., Leukel, C., & Taube, W. (2014). Jump performance and augmented feedback: immediate benefits and long-term training effects. *Human Movement Science*, *36*, 177–189. https://doi.org/10.1016/J.HUMOV.2014.04.007

Kellis, E., & Baltzopoulos, V. (1996). Resistive eccentric exercise: effects of visual feedback on maximum moment of knee extensors and flexors. *Journal of Orthopaedic & Sports Physical Therapy*, *23*(2), 120–124.

Kellis, E., & Blazevich, A. J. (2022). Hamstrings force-length relationships and their implications for angle-specific joint torques: a narrative review. *BMC Sports Science, Medicine and Rehabilitation*, *14*(166), 1–34. https://doi.org/10.1186/s13102-022-00555-6

Kellis, E., Galanis, N., Kapetanos, G., & Natsis, K. (2012). Architectural differences between the hamstring muscles. *Journal of Electromyography* *and Kinesiology*, *22*(4), 520–526. https://doi.org/10.1016/j.jelekin.2012.03.012

Kellis, E., Galanis, N., Kofotolis, N., & Hatzi, A. (2017). Effects of hip flexion angle on surface electromyographic activity of the biceps femoris and semitendinosus during isokinetic knee flexion. *Muscles Ligaments and Tendons Journal*, *2*(7), 286–292.

Kellis, E., & Katis, A. (2008). Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions. *Journal of Electromyography and Kinesiology*, *18*(3), 351–358. https://doi.org/10.1016/J.JELEKIN.2006.12.001

Kenneally-Dabrowski, Claire., Brown, Nicholas., Warmenhoven, John., Serpell, Benjamin., Perriman, Diana., Lai, Adrian., & Spratford, Wayne. (2019). Late swing running mechanics influence hamstring injury susceptibility in elite rugby athletes: a prospective exploratory analysis. *Journal of Biomechanics*, *92*, 112–119. https://doi.org/10.1016/j.jbiomech.2019.05.037

Kenneally-Dabrowski, C., Perriman, Diana., Spratford, Wayne., Brown, Nicholas., Serpell, Benjamin., & Lai, Adrian. (2019). Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scandinavian Journal of Medicine and Science in Sports*, *8*(29), 1–9. https://doi.org/10.1111/sms.13437

Khairunnisa, W., Perdana, S. S., & Azizah, A. N. (2023). The impact of Nordic hamstring exercise on the eccentric strength of hamstring and the length fascicle biceps femoris: systematic review and meta-analysis. *Proceedings of the International Conference on Health and Well-Being (ICHWB 2022)*, *1*, 546–556. https://doi.org/10.2991/978-94-6463-184-5_46

Koller, A., Fuchs, B., Leichtfried, V., & Schobersberger, W. (2015). Decrease in eccentric quadriceps and hamstring strength in recreational alpine skiers after prolonged skiing. *BMJ Open Sport & Exercise Medicine*, *1*(1), 1–6. https://doi.org/10.1136/bmjsem-2015-000028

Konrad, P. (2006). *ABC of EMG: a practical guide to kinesiological electromyography* (1.4). Noraxon Inc. USA.

Kotila, K., Sveinsson, T., & Árnason, Á. (2011). Evidence-based testing of the hamstring muscles using wireless surface EMG. *British Journal of Sports Medicine*, *45*(4), 358–358. https://doi.org/10.1136/BJSM.2011.084038.136

Krommes, K., Jakobsen, M. D., Bandholm, T., Andersen, L. L., Zebis, M., Shield, A., Hölmich, P., & Thorborg, K. (2021). Cross-sectional study of EMG and EMG rise during fast and slow hamstring exercises. *International Journal of Sports Physical Therapy*, *16*(4), 1033–1042. https://doi.org/10.26603/001c.25364

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/FPSYG.2013.00863

Lauber, B., & Keller, M. (2014). Improving motor performance: Selected aspects of augmented feedback in exercise and health. *European Journal of Sport Science*, *14*(1), 36–43. https://doi.org/10.1080/17461391.2012.725104

Lee, J. W. Y., Cai, M. J., Yung, P. S. H., & Chan, K. M. (2018). Reliability, validity, and sensitivity of a novel smartphone-based eccentric hamstring strength test in professional football players. *International Journal of Sports Physiology and Performance*, *13*(5), 620–624. https://doi.org/10.1123/ijspp.2017-0336

Lee, J. W. Y., Li, C., Yung, P. S. H., & Chan, K. M. (2017). The reliability and validity of a video-based method for assessing hamstring strength in football players. *Journal of Exercise Science and Fitness*, *15*(1), 18–21. https://doi.org/10.1016/j.jesf.2017.04.001

Leva De, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, *29*(9), 1223–1230. https://doi.org/1016/0021-9290(95)00178-6.

Lieber, R. L., & Fridén, J. (2002). Mechanisms of muscle injury gleaned from animal models. *American Journal of Physical Medicine and Rehabilitation*, *81*(11), 70–79. https://doi.org/10.1097/00002060-200211001-00008

Liu, H., Garrett, W. E., Moorman, C. T., & Yu, B. (2012). Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: a review of the literature.

Journal of Sport and Health Science, *1*(2), 92–101. https://doi.org/10.1016/j.jshs.2012.07.003

Lloréns, R., Noé, E., Naranjo, V., Borrego, A., Latorre, J., Alcañiz, M., & Baynat, S. (2015). Tracking systems for virtual rehabilitation: objective performance vs. subjective experience. A practical scenario. *Sensors*, *15*, 6586–6606. https://doi.org/10.3390/s150306586

Lodge, C., Tobin, D., Rourke, B. O., & Thorborg, K. (2020). Reliability and validity of a new eccentric hamstring strength measurement device. *Archives of Rehabilitation Research and Clinical Translation*, *2*(1), 1–6. https://doi.org/10.1016/j.arrct.2019.100034

Maeo, S., Huang, M., Wu, Y., Sakurai, H., Kusagawa, Y., Sugiyama, T., Kanehisa, H., & Isaka, T. (2021). Greater hamstrings muscle hypertrophy but similar damage protection after training at long versus short muscle lengths. *Medicine and Science in Sports and Exercise*, *53*(4), 825–837. https://doi.org/10.1249/MSS.0000000000002523

Maniar, N., Carmichael, D. S., Hickey, J. T., Timmins, R. G., San Jose, A. J., Dickson, J., & Opar, D. (2023). Incidence and prevalence of hamstring injuries in field-based team sports: a systematic review and meta-analysis of 5952 injuries from over 7 million exposure hours. *British Journal of Sports Medicine*, *57*(2), 109–116. https://doi.org/10.1136/bjsports-2021-104936

Marshall, P. W. M., Lovell, R., Knox, M. F., Brennan, S. L., & Siegler, J. C. (2015). Hamstring fatigue and muscle activation changes during six sets of Nordic hamstring exercise in amateur soccer players. *Journal of Strength and Conditioning Research*, *29*(11), 3124–3133. https://doi.org/10.1519/JSC.0000000000000966

Marušič, J., Vatovec, R., Marković, G., & Šarabon, N. (2020). Effects of eccentric training at long muscle length on architectural and functional characteristics of the hamstrings. *Scandinavian Journal of Medicine & Science in Sports*. https://doi.org/10.1111/sms.13770

McGrath, T. M., Hulin, B. T., Pickworth, N., Clarke, A., & Timmins, R. G. (2020). Determinants of hamstring fascicle length in professional rugby league athletes. *Journal of Science and Medicine in Sport*, *23*(5), 524–528. https://doi.org/10.1016/j.jsams.2019.12.006

McIntyre, M. (2022). *Hamstring muscle strength assessment and the association with injury risk in Gaelic football*.

Mendiguchia, J., Alentorn-Geli, E., Idoate, F., & Myer, G. D. (2013). Rectus femoris muscle injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. *British Journal of Sports Medicine*, *47*(6), 359–366. https://doi.org/10.1136/bjsports-2012-091250

Mendiguchia, J., Arcos, A. L., Garrues, M. A., Myer, G. D., Yanci, J., & Idoate, F. (2013). The use of MRI to evaluate posterior thigh muscle activity and damage during Nordic hamstring exercise. *Journal of Strength and Conditioning Research*, *27*(12), 3426–3435.

Mendiguchia, J., Conceição, F., Edouard, P., Fonseca, M., Pereira, R., Lopes, H., Morin, J. B., & Jiménez-Reyes, P. (2020). Sprint versus isolated eccentric training: comparative effects on hamstring architecture and performance in soccer players. *PloS One*, *15*(2). https://doi.org/10.1371/JOURNAL.PONE.0228283

Mendiguchia, J., Martinez-Ruiz, E., Edouard, P., Morin, J.-B., Martinez-Martinez, F., Idoate, F., & Mendez-Villanueva, A. (2017). A multifactorial, criteria-based progressive algorithm for hamstring injury treatment. *Medicine & Science in Sports & Exercise*, *49*(7), 1482–1492. https://doi.org/10.1249/MSS.0000000000001241

Mendiguchia, J., Morin, J. B., Samozino, P., Edouard, P., & Alcaraz, P. E. (2015). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine & Science in Sports*, *25*(6), 621–629. https://doi.org/10.1111/sms.12388

Mjølsnes, R., Arnason, A., Østhagen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine and Science in Sports*, *14*(5), 311–317. https://doi.org/10.1046/j.1600-0838.2003.00367.x

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ (Online)*, *339*(7716), 332–336. https://doi.org/10.1136/bmj.b2535

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2017). Analysis of the hamstring muscle activation during two injury prevention exercises. *Journal of Human Kinetics*, *60*(28), 29–37. https://doi.org/10.1515/hukin-2017-0105

Mononen, K., Viitasalo, J. T., Konttinen, N., & Era, P. (2003). The effects of augmented kinematic feedback on motor skill learning in rifle shooting. *Journal of Sports Sciences*, *21*(10), 867–876. https://doi.org/10.1080/0264041031000101944

Morgan, D. L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical Journal*, *57*(2), 209–221. https://doi.org/10.1016/S0006-3495(90)82524-8

Mueller-Wolfhart, H.-W., Haensel, L., Mithoefer, K., Ekstrand, J., English, B., Mcnally, S., Orchard, J., Dijk, C. N. Van, Kerkhoffs, G. M., Schamasch, P., Blottner, D., Swaerd, L., Goedhart, E., & Ueblacker, P. (2013). Terminology and classification of muscle injuries in sport: The Munich consensus statement. *British Journal of Sports Medicine*, *47*(6), 342–350. https://doi.org/10.1136/bjsports-2012-091448

Muggleton, S. (2015). *Master of Applied Science: Kinematics and kinetics of the Nordic hamstring curl* (Issue February).

Muro-de-la-Herran, A., García-Zapirain, B., & Méndez-Zorrilla, A. (2014). Gait analysis methods: an overview of wearable and non-wearable systems, highlighting clinical applications. *Sensors 2014*, *14*(2), 3362–3394. https://doi.org/10.3390/S140203362

Naclerio, F., Larumbe-Zabala, E., Monajati, A., & Goss-Sampson, M. (2015). Effects of two different injury prevention resistance exercise protocols on the hamstring torque-angle relationship: A randomized controlled trial. *Research in Sports Medicine*, *23*(4), 379–393. https://doi.org/10.1080/15438627.2015.1076418

Nixon, M. A., McCallum, B. C., Fright, W. R., & Price, N. B. (1998). The effects of metals and interfering fields on electromagnetic trackers. *Presence: Teleoperators and Virtual Environments*, *7*(2), 204–218. https://doi.org/10.1162/105474698565587

Nunes, H., Fernandes, L. G., Martins, P. N., & Ferreira, R. M. (2024). The effects of Nordic hamstring exercise on performance and injury in the lower extremities: an umbrella review. *Healthcare*, *12*(15). https://doi.org/10.3390/HEALTHCARE12151462

Ogborn, D. I., Bellemare, A., Bruinooge, B., Brown, H., McRae, S., & Leiter, J. (2021). Comparison of common methodologies for the determination of knee flexor Muscle Strength. *International Journal of Sports Physical Therapy*, *16*(2), 350. https://doi.org/10.26603/001C.21311

Oliver, G. D., & Dougherty, C. P. (2009). The razor curl: a functional approach to hamstring training. *Journal of Strength and Conditioning Research*, *23*(2), 401–405.

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: A reliability and retrospective injury study. *Journal of Orthopaedic & Sports Physical Therapy*, *43*(9), 636–640. https://doi.org/10.2519/jospt.2013.4837

Opar, D. A., Williams, M. D., & Shield, A. J. (2012). Hamstring strain injuries: factors that lead to injury and re-Injury. *Sports Medicine*, *42*(3), 209–226. https://doi.org/10.2165/11594800-000000000-00000

Opar, D. A., Williams, M. D., Timmins, R. G., Dear, N. M., & Shield, A. J. (2013). Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *Journal of Electromyography and Kinesiology*, *23*(3), 696–703. https://doi.org/10.1016/J.JELEKIN.2012.11.004

Opar, D. A., Williams, M. D., Timmins, R. G., Hickey, J., Duhig, S. J., & Shield, A. J. (2015). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, *47*(4), 857–865. https://doi.org/10.1249/MSS.0000000000000465

Opar, D. A., Williams, M., Piatkowski, T., & Shield, A. (2013). A novel field test of eccentric hamstring strength: A reliability and injury study. *Journal of Science and Medicine in Sport*, *16*, e41. https://doi.org/10.1016/j.jsams.2013.10.098

Oranchuk, D. J., Storey, A. G., Nelson, A. R., & Cronin, J. B. (2019). Isometric training and long- term adaptations: effects of muscle length, intensity, and intent: A systematic review. *Scandinavian Journal of Medicine & Science in Sports*, *29*(4), 484–503. https://doi.org/10.1111/sms.13375

Orchard, J., Marsden, J., Lord, S., & Garlick, D. (1997). Preseason hamstring muscle weakness associated with hamstring muscle injury in australian footballers. *American Journal of Sports Medicine*, *25*(1), 81–85. https://doi.org/10.1177/036354659702500116

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the Australian football league, seasons 1997–2000. *British Journal of Sports Medicine*, *36*, 39–45. https://doi.org/http://dx.doi.org/10.1136/bjsm.36.1.39

Örer, G. E., Güzel, N. A., & Arslan, E. (2016). Recovery levels after eccentric and concentric loading in maximal force. *Journal of Physical Therapy Science*, *28*(6), 1743. https://doi.org/10.1589/JPTS.28.1743

Park, S., Kim, S., & Park, D. (2019). Effect of slope angle on muscle activity during variations of the Nordic exercise. *Journal of Exercise Rehabilitation*, *15*(6), 832–838. https://doi.org/10.12965/jer.1938670.335

Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men’s soccer: a cluster-randomized controlled trial. *American Journal of Sports Medicine*, *39*(11), 2296–2303. https://doi.org/10.1177/0363546511419277

Phillips, E., Farrow, D., Ball, K., & Helmer, R. (2013). Harnessing and understanding feedback technology in applied settings. *Sports Medicine*, *10*(43), 919–925. https://doi.org/10.1007/s40279-013-0072-7

Pollard, C. W., Bourne, M. N., Timmins, R. G., & Opar, D. A. (2019). Razor hamstring curl and Nordic hamstring exercise architectural adaptations:

Impact of exercise selection and intensity. *Scandinavian Journal of Medicine & Science in Sports*, *29*(5), 706–715. https://doi.org/10.1111/sms.13381

Potier, T. G., Alexander, C. M., & Seynnes, O. R. (2009). Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *European Journal of Applied Physiology*, *105*(6), 939–944. https://doi.org/10.1007/s00421-008-0980-7

Poulin, F., & Amiot, L. P. (2002). Interference during the use of an electromagnetic tracking system under OR conditions. *Journal of Biomechanics*, *35*(6), 733–737. https://doi.org/10.1016/S0021-9290(02)00036-2

Presland, J. D., Timmins, R. G., Bourne, M. N., Williams, M. D., & Opar, D. A. (2018). The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scandinavian Journal of Medicine & Science in Sports*, *28*(7), 1775–1783. https://doi.org/10.1111/sms.13085

Raiteri, B. J., Beller, R., & Hahn, D. (2021). Biceps femoris long head muscle fascicles actively lengthen during the Nordic hamstring exercise. *Frontiers in Sports and Active Living*, *3*(June), 1–10. https://doi.org/10.3389/fspor.2021.669813

Ripley, N. J., Cuthbert, M., Ross, S., Comfort, P., & McMahon, J. J. (2021a). The effect of exercise compliance on risk reduction for hamstring strain injury: a systematic review and meta-analyses. *International Journal of Environmental Research and Public Health*, *18*(21), 1–16. https://doi.org/10.3390/ijerph182111260

Ripley, N. J., Cuthbert, M., Ross, S., Comfort, P., & McMahon, J. J. (2021b). The effect of exercise compliance on risk reduction for hamstring strain injury: a systematic review and meta-analyses. *International Journal of Environmental Research and Public Health*, *18*(21), 1–16. https://doi.org/10.3390/ijerph182111260

Ripley, N. J., Fahey, J., Comfort, P., & McMahon, J. (2024). Kinematic, Neuromuscular and Bicep Femoris In Vivo Mechanics during the Nordic

Hamstring Exercise and Variations of the Nordic Hamstring Exercise. *Muscles*, *3*(3), 310–322. https://doi.org/10.3390/muscles3030027

Robson, C. (2011). *Real world research: A resource for users of social research methods in applied settings (2nd Ed.)* (A. Sussex, Ed.). John Wiley and Sons Ltd.

Roe, M., Delahunt, E., Malone, S., Collins, K., Mchugh, M., & Blake, C. (2020). Association between eccentric knee flexor strength and hamstring injury risk in 185 elite Gaelic football players. *Scandinavian Journal of Medicine & Science in Sports*, *30*(3), 515–522. https://doi.org/10.1111/sms.13588

Ruddy, J. D., Shield, A. J., Maniar, N., Williams, M. D., Duhig, S., Timmins, R. G., Hickey, J., Bourne, M. N., & Opar, D. A. (2018). *Predictive Modeling of Hamstring Strain*. *50*(5), 906–914. https://doi.org/10.1249/MSS.0000000000001527

Šarabon, N., Marušič, J., Marković, G., & Kozinc, Ž. (2019). Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. *PLOS ONE*, *14*(10), 1–16. https://doi.org/10.1371/journal.pone.0223437

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise*, *44*(4), 647–658. https://doi.org/10.1249/MSS.0b013e318236a3d2

Schache, A. G., Kim, H., Morgan, D. L., & Pandy, M. G. (2010). Hamstring muscle forces prior to and immediately following an acute sprinting-related muscle strain injury. *Gait & Posture*, *32*(1), 136–140. https://doi.org/10.1016/j.gaitpost.2010.03.006

Schmitt, B., Tim, T., & McHugh, M. (2012). Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. *International Journal of Sports Physical Therapy*, *7*(3), 333–341. https://doi.org/10.1016/j.jsams.2013.10.016

Schober, P., & Schwarte, L. A. (2018). Correlation coefficients: appropriate use and interpretation. *Anesthesia and Analgesia*, *126*(5), 1763–1768. https://doi.org/10.1213/ANE.0000000000002864

Schuermans, J., Van Tiggelen, D., Danneels, L., & Witvrouw, E. (2014). Biceps femoris and semitendinosus - teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study. *British Journal of Sports Medicine*, *48*(22), 1599–1606. https://doi.org/10.1136/bjsports-2014-094017

Sconce, E., Heller, B., Maden-Wilkinson, T., & Hamilton, N. (2021a). Agreement between methods and terminology used to assess the kinematics of the Nordic hamstring exercise. *Journal of Sports Sciences*, *39*(24), 2859–2868. https://doi.org/10.1080/02640414.2021.1968127

Sconce, E., Heller, B., Maden-Wilkinson, T., & Hamilton, N. (2021b). Development of a novel Nordic hamstring exercise device to measure and modify the knee flexors' torque-length relationship. *Frontiers in Sports and Active Living*, *3*(629606), 1–9. https://doi.org/10.3389/fspor.2021.629606

Sconce, E., Heller, B., Maden-Wilkinson, T., & Hamilton, N. (2024). Examining the effect of verbal feedback vs. real-time software feedback on kinetic and kinematic metrics of the Nordic hamstring exercise. *Sport Sciences for Health*. https://doi.org/10.1007/s11332-024-01294-6

Sconce, E., Jones, P., Turner, E., Comfort, P., & Graham-Smith, P. (2015). The validity of the Nordic hamstring lower for a field-based assessment of eccentric hamstring strength. *Journal of Sport Rehabilitation*, *24*(1), 13–20. https://doi.org/10.1123/jsr.2013-0097

Seymore, K. D., Domire, Z. J., DeVita, P., Rider, P. M., & Kulas, A. S. (2017). The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. *European Journal of Applied Physiology*, *117*(5), 943–953. https://doi.org/10.1007/s00421-017-3583-3

Seynnes, O. R., De Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *Journal of Applied Physiology*, *102*(1), 368–373. https://doi.org/10.1152/japplphysiol.00789.2006.

Sharifnezhad, A., Marzilger, R., & Arampatzis, A. (2014). Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle. *Journal of Experimental Biology*, *217*(15), 2726–2733. https://doi.org/10.1242/jeb.100370

Shield, A., & Bourne, M. (2018). Hamstring injury prevention practices in elite sport: evidence for eccentric strength vs. lumbo-pelvic training. *Sports Medicine*, *48*(3), 513–524. https://doi.org/10.1007/s40279-017-0819-7

Shield, A., & Murphy, S. (2018). Preventing hamstring injuries - Part 1: Is there really an eccentric action of the hamstrings in high-speed running and does it matter? *Sport Performance & Science Reports*, *25*(1), 1–5.

Siddle, J., Greig, M., Weaver, K., Page, R. M., Brogden, C. M., Siddle, J., Greig, M., Weaver, K., & Page, R. M. (2018). Acute adaptations and subsequent preservation of strength and speed measures following a Nordic hamstring curl intervention: a randomised controlled trial. *Journal of Sports Sciences*, *00*(00), 1–10. https://doi.org/10.1080/02640414.2018.1535786

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2012). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. https://doi.org/10.3758/S13423-012-0333-8

Singh, A. S. (2014). Conducting case study research in non-profit organisations. *Qualitative Market Research*, *17*(1), 77–84. https://doi.org/10.1108/QMR-04-2013-0024

Smet De, A. A., & Best, T. M. (2000). MR imaging of the distribution and location of acute hamstring injuries in athletes. *American Journal of Roentgenology*, *174*(2), 393–399. https://doi.org/10.2214/ajr.174.2.1740393

Soga, T., Hakariya, N., Saito, H., Nakaichi, N., Akiyama, K., & Hirose, N. (2023). Electromyographic activity of hip extensor muscles during Nordic hamstring and razor curl exercises on levelled and inclined shanks. *Sport Sciences for Health*. https://doi.org/10.1007/s11332-023-01113-4

Soga, T., Nishiumi, D., Furusho, A., Akiyama, K., & Hirose, N. (2021). Effect of different slopes of the lower leg during the Nordic hamstring exercise on hamstring electromyography activity. *Journal of Sports Science and Medicine*, *20*, 216–221. https://doi.org/10.52082/jssm.2021.216

Soga, T., Yamaguchi, S., Inami, T., Saito, H., Hakariya, N., Nakaichi, N., Shinohara, S., Sasabe, K., Nakamura, H., Laddawong, T., Akiyama, K., & Hirose, N. (2023). Hamstring activity before and after break-point angle calculated by smartphone application during the Nordic hamstring exercise. *International Journal of Sports Physical Therapy*, *18*(6), 1290–1298. https://doi.org/10.26603/001c.89271

Sorzano, C. O. S., Tabas-Madrid, D., Núñez, F., Fernández-Criado, C., & Naranjo, A. (2017). Sample size for pilot studies and precision driven experiments. *Laboratory Animals*. https://arxiv.org/pdf/1707.00222

Sousa, F., Ishikawa, M., & Komi, P. V. (2007). Intensity and muscle specific fascicle behavior during human drop jumps. *Journal of Applied Physiology*, *102*(1), 382–389. https://doi.org/10.1152/japplphysiol.00274.2006.

Souza Oliveira, A., & Pirscoveanu, C. I. (2021). Implications of sample size and acquired number of steps to investigate running biomechanics. *Scientific Reports*, *11*(1), 3083. https://doi.org/10.1038/s41598-021-82876-z

Spendiff, O., Longford, N. T., & Winter, E. M. (2002). Effects of fatigue on the torque-velocity relation in muscle. *British Journal of Sports Medicine*, *36*(6), 431–435. https://doi.org/10.1136/BJSM.36.6.431

Sugiura, Y., Saito, T., Sakuraba, K., Sakuma, K., & Suzuki, E. (2008). Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *Journal of Orthopaedic & Sports Physical Therapy*, *38*(8), 457–464. https://doi.org/10.2519/jospt.2008.2575

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2*, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L., Young, M., & Heiderscheit, B. C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise*, *37*(1), 108–114. https://doi.org/10.1249/01.MSS.0000150078.79120.C8

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *British Journal of Sports Medicine*, *50*(24), 1524–1535. https://doi.org/10.1136/bjsports-2015-095362

Timmins, R. G., Ruddy, J. D., Presland, J., Maniar, N., Shield, A. J., Williams, M. D., & Opar, D. A. (2016). Architectural changes of the biceps femoris long head after concentric or eccentric training. *Medicine & Science in Sports & Exercise*, *48*(3), 499–508. https://doi.org/10.1249/MSS.0000000000000795

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *British Journal of Sports Medicine*, *50*(23), 1467–1472. https://doi.org/10.1136/bjsports-2015-094881

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, Christian., & Opar, D. A. (2015). Biceps femoris long head architecture: a reliability and retrospective injury study. *Medicine and Science in Sports and Exercise*, *47*(5), 905–913. https://doi.org/10.1249/MSS.0000000000000507

Tirrell, T. F., Rademaker, A. W., & Lieber, R. L. (2018). Analysis of hierarchical biomechanical data structures using mixed-effects models. *Journal of Biomechanics*, *69*, 34–39. https://doi.org/10.1016/J.JBIOMECH.2018.01.013

Toro Del, S. F., Wei, Y., Olmeda, E., Ren, L., Guowu, W., & Díaz, V. (2019). Validation of a low-cost electromyography (EMG) system via a commercial and accurate EMG device: pilot study. *Sensors (Switzerland)*, *19*(23). https://doi.org/10.3390/s19235214

Torrejón, L. N., Martínez-Serrano, A., Villalón, J. M., & Alcaraz, P. E. (2024). Economic impact of muscle injury rate and hamstring strain injuries in professional football clubs. Evidence from LaLiga. *PLoS ONE*, *19*(6). https://doi.org/10.1371/journal.pone.0301498

Turner, E., Munro, A. G., & Comfort, P. (2013). Female soccer: Part 2 - Training considerations and recommendations. *Strength and Conditioning Journal*, *35*(1), 58–65. https://doi.org/10.1519/SSC.0b013e318282106d

Tyler, T. F., Schmitt, B. M., Nicholas, S. J., & McHugh, M. P. (2017). Rehabilitation after hamstring strain injury emphasizing eccentric strengthening at long muscle lengths: results of long-term follow-up. *Journal of Sport Rehabilitation*, *26*(2), 131–140.

Vagenas, G., Palaiothodorou, D., & Knudson, D. (2018). Thirty-year trends of study design and statistics in applied sports and exercise biomechanics research. *International Journal of Exercise Science*, *11*(1), 239–259. http://www.intjexersci.com

VALD performance. European football report season 2019-20: Nordic strength. (2020). https://valdperformance.com/news/nordic-strength

VALD performance: Female professional athletes: Nordic and hip ad/ab results. (2021). https://valdperformance.com/news/aflw-normative-data-nordic-hip-adduction-and-cmj-results

VALD performance: NordBord specification. (2025). https://support.vald.com/hc/en-au/articles/4808165517849-NordBord-Technical-Specifications

Valle, X., Tol, J. L., Hamilton, B., Rodas, G., Malliaras, P., Malliaropoulos, N., Rizo, V., Moreno, M., & Jardi, J. (2015). Hamstring muscle injuries, a rehabilitation protocol purpose. *Asian Journal of Sports Medicine*, *6*(4), 1–11. https://doi.org/10.5812/asjsm.25411

Van Der Horst, N., Smits, D. W., Petersen, J., Goedhart, E. A., & Backx, F. J. G. (2015). The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *American Journal of Sports Medicine*, *43*(6), 1316–1323. https://doi.org/10.1177/0363546515574057

Van Der Horst, N., Van De Hoef, S., Otterloo, P. V, & Klein, M. (2021). Effective but not adhered to: how can we improve adherence to evidence-based hamstring injury prevention in amateur football? *Clinical Journal of Sports Medicine*, *31*(1), 42–48.

Van Dyk, N., Bahr, R., Burnett, A. F., Whiteley, R., Bakken, A., Mosler, A., Farooq, A., & Witvrouw, E. (2017). A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: a prospective cohort study of 413 professional football players. *British Journal of Sports Medicine*, *51*(23), 1695–1702. https://doi.org/10.1136/bjsports-2017-097754

Van Dyk, N., Bahr, R., Whiteley, R., Tol, J. L., Kumar, B. D., Hamilton, B., Farooq, A., & Witvrouw, E. (2016). Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries. *American Journal of Sports Medicine*, *44*(7), 1789–1795. https://doi.org/10.1177/0363546516632526

Van Dyk, N., Behan, F. P., & Whiteley, R. (2019). Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *British Journal of Sports Medicine*, *53*(21), 1362–1370. https://doi.org/10.1136/bjsports-2018-100045

Van Dyk, N., Witvrouw, E., & Bahr, R. (2018). Interseason variability in isokinetic strength and poor correlation with Nordic hamstring eccentric strength in football players. *Scandinavian Journal of Medicine & Science in Sports*, *28*(8), 1878–1887. https://doi.org/10.1111/sms.13201

Van Hooren, B., & Bosch, F. (2016). Influence of muscle slack on high-intensity sport performance: a review. *National Strength and Conditioning Association*, *38*(5), 75–87.

Van Hooren, B., & Bosch, F. (2017). Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? Part II: Implications for exercise. *Journal of Sports Sciences*, *35*(23), 2322–2333. https://doi.org/10.1080/02640414.2016.1266019

Van Hooren, B., & Bosch, F. (2018). Preventing hamstring injuries Part 2: There is possibly an isometric action of the hamstrings in high-speed running and it does matter. *Sport Performance & Science Reports*, *25*(1), 1–5.

Van Hooren, B., Vanwanseele, B., Rossom, S., Teratsias, P., Willems, P., Drost, M., & Meijer, K. (2022). Muscle forces and fascicle behavior during three hamstring exercises. *Scandinavian Journal of Medicine & Science in Sports*. https://doi.org/10.1111/sms.14158

Vaz, L., Kraak, W., Batista, M., Honório, S., & Fernandes, H. M. (2021). Using anthropometric data and physical fitness scores to predict selection in a national u19 rugby union team. *International Journal of Environmental Research and Public Health*, *18*(4), 1–8. https://doi.org/10.3390/ijerph18041499

Verrall, G. M. (2001). Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine*, *35*(6), 435–439. https://doi.org/10.1136/bjsm.35.6.435

Vianna, K. B., Rodrigues, L. G., Oliveira, N. T., Ribeiro-Alvares, J. B., & Baroni, B. M. (2021). A preseason training program with the nordic hamstring exercise increases eccentric knee flexor strength and fascicle length in professional female soccer players. *International Journal of Sports Physical Therapy*, *16*(2), 459–467. https://doi.org/10.26603/001c.19452

Vicente-Mampel, J., Bautista, I. J., Martín, F., Maroto-, S., Hooren, B. Van, Baraja-vegas, L., Bautista, I. J., Martín, F., Maroto-, S., & Maroto-izquierdo, S. (2022). Effects of ankle position during the nordic hamstring exercise on range of motion, heel contact force and hamstring muscle activation. *Sports Biomechanics*, 1–13. https://doi.org/10.1080/14763141.2021.2025416

Visser, H. M. De, Reijman, M., Heijboer, M. P., & Bos, P. K. (2012). Risk factors of recurrent hamstring injuries: a systematic review. *British Journal of Sports Medicine*, *46*(2), 124–130. https://doi.org/10.1136/bjsports-2011-090317

Wackerly, D. D., Mendenhall, W., Scheaffer, R. L., & Cohen, S. B. (2008). *Mathematical Statistics with Applications: Vol. 7th Edition*.

Walsh, L., O'Brien, J., & Browne, D. (2024). A comparison of force production in eccentric hamstring exercises. *International Journal of Strength and Conditioning*, *4*(1), 1–13. https://doi.org/10.47206/ijsc.v4i1.298

Watanabe, K., Kouzaki, M., & Moritani, T. (2016). Effect of electrode location on task-dependent electromyography responses within the human biceps femoris muscle. *Journal of Applied Biomechanics*, *32*(1). https://doi.org/10.1123/jab.2015-0017

Weakley, J., Cowley, N., Schoenfeld, B. J., Read, D. B., Timmins, R. G., García-Ramos, A., & McGuckian, T. B. (2023). The effect of feedback on resistance training performance and adaptations: a systematic review and meta-analysis. *Sports Medicine*, *9*(53), 1789–1803. https://doi.org/10.1007/s40279-023-01877-2

Weygers, Ive., Kok, Manon., Konings, Marco., Hallez, Hans., De Vroey, Henri., & Claeys, Kurt. (2020). Inertial sensor-based lower limb joint kinematics: a methodological systematic review. *Sensors*, *20*(3), 673. https://doi.org/10.3390/S20030673

Wheare, M. J., Nelson, M. J., Lumsden, R., Buttfield, A., & Crowther, R. G. (2021). Reliability and validity of the polhemus liberty system for upper body segment and joint angular kinematics of elite golfers. *Sensors (Basel, Switzerland)*, *21*(13), 4330. https://doi.org/10.3390/S21134330

Wiesinger, H. P., Müller, E., Gressenbauer, C., & Kösters, A. (2020). Device and method matter: a critical evaluation of eccentric hamstring muscle strength assessments. *Scandinavian Journal of Medicine & Science in Sports*, *30*(2), 217–226. https://doi.org/10.1111/sms.13569

Wiesinger, H. P., Scharinger, M., Kösters, A., Gressenbauer, C., & Müller, E. (2021). Specificity of eccentric hamstring training and the lack of consistency between strength assessments using conventional test devices. *Scientific Reports*, *11*(1), 1–13. https://doi.org/10.1038/s41598-021-92929-y

Wilk, M., Zajac, A., & Tufano, J. J. (2021). The influence of movement tempo during resistance training on muscular strength and hypertrophy responses:

a review. *Sports Medicine*, *51*(8), 1629–1650. https://doi.org/10.1007/s40279-021-01465-2

Woodley, S. J., & Mercer, S. R. (2005). Hamstring muscles: architecture and innervation. *Cells Tissues Organs*, *179*(3), 125–141. https://doi.org/10.1159/000085004

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., & Hodson, A. (2004). The football association medical research programme: an audit of injuries in professional football - analysis of hamstring injuries. *British Journal of Sports Medicine*, *38*(1), 36–41. https://doi.org/10.1136/bjsm.2002.002352

Wu, W. F. W., Porter, J. M., & Brown, L. E. (2012). Effect of attentional focus strategies on peak force and performance in the standing long jump. *Journal of Strength and Conditioning Research*, *26*(5), 1226–1231.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, *6*(1), 77. https://doi.org/10.1080/1750984X.2012.723728

Yaniv, Z., Wilson, E., Lindisch, D., & Cleary, K. (2009). Electromagnetic tracking in the clinical environment. *Medical Physics*, *36*(3), 876–892. https://doi.org/10.1118/1.3075829

Yeung, S. S., Suen, A. M. Y., & Yeung, E. W. (2009). A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *British Journal of Sports Medicine*, *43*(8), 589–594. https://doi.org/10.1136/bjsm.2008.056283

Yu, B., Queen, R. M., Abbey, A. N., Liu, Y., Moorman, C. T., & Garrett, W. E. (2008). Hamstring muscle kinematics and activation during overground sprinting. *Journal of Biomechanics*, *41*(15), 3121–3126. https://doi.org/10.1016/j.jbiomech.2008.09.005

Zakas, A. (2006). Bilateral isokinetic peak torque of quadriceps and hamstring muscles in professional soccer players with dominance on one or both two sides. *Journal of Sports Medicine and Physical Fitness*, *46*(1), 28–35.

Zehr, E. P., & Sale, D. G. (1994). Ballistic movement: muscle activation and neuromuscular adaptation. *Canadian Journal of Applied Physiology*, *19*(4), 363–378. https://doi.org/10.1139/h94-030