The Influence of Weekly Sprint Volume and Maximal Velocity Exposures on Eccentric Hamstring Strength in Professional Football Players

By

Sunnan Shah

Master of Philosophy
in
Sports Studies

Faculty of Health Sciences and Sport
University of Stirling

Submitted: January 2022

In the name of God, Most Merciful and Compassionate

"The traveller on the path to truth must have intelligence, understanding and insight.
These are his prerequisites."

Hadrat Abdul-Qadir al-Jilani

Acknowledgments

I would like to thank all players and staff who were directly or indirectly involved in this study, particularly Kevin Symon and the rest of the Medical and Sports Science Department. I am grateful to my supervisors Dr Lewis Macgregor and Dr Angus Hunter for their guidance, particularly the former, who was extremely helpful throughout and beyond the study and was always on hand when required for support. Finally, I would like to thank my brother Dr Nadeem Wasif Shah for his valuable advice and help throughout the final stages of this thesis.

Abstract

Background: Hamstring strains are the most common injuries of moderate and major severity in football. To reduce the risk of these injuries it is important to understand the mechanisms and risk factors that cause them. Sprinting is the primary cause of hamstring injuries, with eccentric hamstring strength identified as a risk factor. **Objective:** To identify any relationships between sprinting and eccentric hamstring strength by investigating the influence of total weekly sprint distance (m) and weekly efforts >90% and >95% of an individual's maximum velocity on the eccentric force output of the hamstring muscles. **Methods:** Fifty-eight professional male football players were observed over one and a half football seasons. The players' weekly movements and speeds were monitored during training and matches using GPS, while eccentric hamstring strength was measured during the Nordic Hamstring Exercise, on the NordBord, as part of their weekly strength and conditioning session. **Results:** Weekly sprint distance ($\rho = -0.13$, $P < 0.01$) and weekly efforts >90% of maximum velocity ($\rho = -0.08$, $P = 0.01$) both had significant inverse relationships with percentage change in eccentric hamstring strength, with very small correlations; however, total weekly efforts >95% of maximum velocity showed no relationship ($\rho = -0.02$, $P = 0.45$). Only weekly efforts >90% of maximum velocity significantly influenced the mean percentage change in eccentric hamstring force, $F_{(3, 58)} = 3.71$, $P = 0.01$, with significant differences occurring when comparing 7-8 sprint efforts with 0-2 efforts (0.11%, $P = 0.03$) and 5-6 efforts (0.12%, $P = 0.03$). **Conclusion:** Eccentric hamstring strength levels significantly decrease when 7-8 weekly sprint efforts are completed at a maximum velocity >90% but are not significantly influenced by total weekly sprint distance or the weekly number of sprint efforts completed at a maximum velocity >95%.

Key Words: Hamstring, injury risk, eccentric strength, sprint distance, sprint efforts, Nordic Hamstring Exercise, NordBord, GPS

Confirmation of Ethical Approval

This study was approved by the NHS, Invasive or Clinical Research Committee (NICR) at the University of Stirling (18/19 -004).

Table of Contents

Acknowledgments..**2**

Abstract..**3**

Confirmation of Ethical Approval..**3**

List of Tables and Figures...**6**

Glossary and List of Abbreviations...**8**

1. Introduction...**10**

1.1 Musculoskeletal Injuries: Effects and Implications in Sport..................*10*

1.2 Musculoskeletal Injuries in Football..*11*

1.3 Hamstring Musculature and Mechanisms of Injury...............................*12*

1.4 Training the Hamstring Muscles...*14*

1.4.1 Strength Training...14

1.4.2 Reliability and Validity of Hamstring Testing Devices..........................16

1.4.3 Speed Exposures: Monitoring and Preparing Athletes...........................17

1.4.4 Demands of the Game..18

1.5 Objective and Aim of Study..*20*

1.6 Hypothesis..*20*

2. Methods..**21**

2.1 Participants..*21*

2.2 Study Design...*22*

2.3 Protocol...*22*

2.3.1 Sprint Monitoring...22

2.3.2 Nordic Hamstring Exercise..23

2.4 Statistical Analysis...*26*

2.5 Reliability of NordBord..*26*

2.6 Validity of NordBord..*27*

3. Results..**28**

3.1 Participant Data *28*

3.2 Relationship Between Sprinting and Hamstring Strength *29*

3.3 Reliability and Validity of NordBord *31*

4. Discussion **34**

4.1 Main Findings *34*

4.2 Reliability and Validity *35*

4.3 Weekly Efforts at 90% of Maximum Velocity *37*

4.4 Weekly Efforts at 95% of Maximum Velocity *38*

4.5 Weekly Sprint Distance *39*

4.6 Sprinting and Hamstring Strength Trends in Football *40*

4.7 Limitations and Practical Implications *43*

5. Conclusion **44**

6. References **45**

7. Appendices **58**

List of Tables and Figures

Tables

Table 1. Profile of participants (Mean ± SD) 22

Table 2. Sprinting profile of players using GPS data. Data are presented based on the players' playing positions and as a collective group (Mean ± SD) 28

Table 3. Hamstring strength profile of players using NordBord data. Data are presented based on the players' playing positions and as a collective group (Mean ± SD) 29

Table 4. Spearman correlation (ρ) between percentage change in eccentric hamstring force compared with weekly sprint distance (m), weekly efforts >90% of maximum velocity and weekly efforts >95% of maximum velocity..29

Table 5. Average of right and left limb eccentric hamstring strength of each participant during intra-day (Tests 1 & 2) and inter-day (Tests 1 & 3) reliability of the NordBord...32

Table 6a. Descriptive statistics of isometric hamstring strength testing on IKD and NordBord for validity (n = 6) 32

Table 6b. Descriptive statistics of eccentric hamstring strength testing on IKD and NordBord for validity (n = 6) 33

Figures

Figure 1. Rear view of the thigh showing the anatomy of the hamstring muscles (highlighted in red) (adapted from Van der Horst, 2017)..13

Figure 2. The phases of the Sprint Cycle (taken from Kalkhoven et al., 2020) 13

Figure 3. Performing Nordic Hamstring Exercise with a partner.....................................15

Figure 4. NordBord Hamstring Testing System, Vald Performance.................................24

Figure 5. Trace of NHE on Vald Performance's ScoreBord software 24

Figure 6. How to select a NordBord knee position...25

Figure 7. Performing the Nordic Hamstring Exercise on NordBord. (A) Starting in upright position, (B) contracting knee flexors during movement to control descent, (C) finishing by placing hands on ground after breaking point; all while ankles are secured by hooks attached to load cells. 25

Figure 8. Video showing how to perform Nordic Hamstring Exercise on NordBord.......25

Figure 9. The mean percentage change in eccentric hamstring force in relation to total weekly sprint distance (m)..30

Figure 10. The mean percentage change in eccentric hamstring force in relation to weekly sprint efforts >90% of maximum velocity (* denotes significance between 0-2 and 7-8 efforts; † denotes significance between 5-6 and 7-8 efforts, P<0.05) 31

Figure 11a. Maximum eccentric force (N) of left and right limb combined; IKD vs NordBord 34

Figure 11b. Maximum eccentric force (N), mean of left and right limb; IKD vs NordBord 34

Appendix A. Injury pattern with severity of injuries (adapted from Ekstrand et al., 2011) 58

Appendix B. Review of positional differences for total, high-speed running and sprint distances covered during match-play in various leagues (mean ± SD)............................59

Glossary and List of Abbreviations

Dashboard – Vald Performance's online platform where post-test results are uploaded for monitoring purposes and further analysis

Eccentric Contraction – When a force is applied to the muscle which exceeds the force produced by the muscle itself, resulting in the forced lengthening of the muscle-tendon system while contracting

Eccentric Strength – The ability to contract the muscle as much as possible while it is lengthening

Effort at Max$_{>90\%}$ – An occasion where a player has reached 90% of his maximum velocity for a duration greater than 0.6 seconds

Effort at Max$_{>95\%}$ – An occasion where a player has reached 95% of his maximum velocity for a duration greater than 0.6 seconds

Force Output – The strength/power exerted during a movement in Newtons (N)

High Speed/Intensity Running – Running at a speed between 5.5 – 7 m/s for any given distance

High Velocity Running – Running at near maximal speeds, generally greater than 85% of a player's maximum velocity

Isometric Contraction – A muscle contraction without motion required to stabilise a joint, causing the muscle to maintain the same length

Load – The stress placed on the body during physical activity

Maximum Velocity – The fastest speed achieved by the player at any one point during the duration of the study

Musculoskeletal Injury – An injury affecting muscles, bones or connective tissue

NordBord – Apparatus designed by Vald Performance to measure physical outputs of the hamstring muscles

ScoreBord – Vald Performance’s software showing live parameters while performing any exercise on the NordBord

Spike – When the short term (acute) workload drastically exceeds the long term (chronic) workload

Sprint Distance – The total distance covered at a speed greater than 7 m/s

NHE – Nordic Hamstring Exercise

GPS – Global Positioning System

ACWR – Acute:Chronic Workload Ratio

IKD – Isokinetic Dynamometer

SSG’s – Small Sided Games

Max$_{>85\%}$ –a velocity greater than 85% of a players’ maximum speed

Max$_{>90\%}$ –a velocity greater than 90% of a players’ maximum speed

Max$_{>95\%}$ –a velocity greater than 95% of a players’ maximum speed

CV – Coefficient of Variation

ICC – Intraclass Correlation Coefficient

1. Introduction

1.1 Musculoskeletal Injuries: Effects and Implications in Sport

Musculoskeletal injuries are the leading contributor to disability worldwide (World Health Organisation, 2019). Globally, it has been found that musculoskeletal injuries account for 20.8% of disabilities, while in the UK that value rises to 30.5% (Vos et al., 2015; Murray et al., 2013). It is also estimated that a combined total of 138 million years are lived with a disability caused by a musculoskeletal injury (Vos et al., 2017). According to the International Classification of Diseases, musculoskeletal injuries affect the muscles, bones, joints and associated tissues such as tendons and ligaments. Although, a high proportion of these injuries are found in the elderly population, many younger individuals are also affected (Public Health England, 2018; National Health Interview Survey, 2012). These cases are mostly linked with inactivity, where a sedentary lifestyle has been shown to increase the risk of developing a musculoskeletal injury, particularly associated with the lower back (Hootman et al.,2001; Taanila et al., 2015). Conversely, high levels of activity have also been linked with an increased risk of injury, and so the sporting environment can often be a cause of these injuries; however, the site of injury is found to be predominantly in the lower extremities rather than in the back (Hootman et al., 2001).

Sport has many health benefits such as improving cardiovascular function and muscular adaptation which can in turn reduce the risk of musculoskeletal injuries (Oja et al., 2015). However, in many cases, particularly in professional sport, it can also increase the risk of injury due to the high physical demands of training and competition, and collisions associated with contact sports (Bangsbo et al., 2006; Povoas et al., 2012; Gabbett et al., 2012). These risks can apply to the general population involved in recreational sport and those who are involved professionally. However, for a professional athlete the consequences of injury can be severe, with many social and economic implications. An athlete's career can be short, where on average the retirement age is approximately 30 years (Stambulova et al., 2007). With an already limited time to make a living, injuries can further reduce an athlete's career resulting in a loss of income for them and their dependents, which can then cause them to suffer from the associated social repercussions often resulting in mental health issues. There are also implications for the health services and sporting organisations affiliated with the athlete. There can be direct costs involved, such as for drugs, physiotherapy, hospital admissions and surgery causing a huge financial burden to those involved (Cumps et al., 2008). There are also indirect costs resulting from reduced productivity in the workplace, often leading to loss of employment or early retirement (Parsons & Symmons, 2014). The financial values are not insignificant either, with some top-level athletes worth up to $127 million (Forbes, 2019). Many of the athletes leading Forbes' list are involved in football, which is the most popular sport in the world and one of the most profitable. Globally, football has the largest fan base of any sport with an estimated four billion fans (Shvili, 2020). Due to this popularity, football generates more revenue than any other sport, mainly through television broadcasting deals, sponsorships and betting (Forbes, 2019). Due to the amount of investments made by fans, sporting organisations and other stakeholders, the importance of success is paramount for each team. Success can be determined in a number of ways and there are many factors that influence it, with winning being the ultimate goal (Lepschy et al., 2018). Injury occurrence is one of the factors found to influence success, where more injuries have shown to have a negative impact on the performance of the team (Hagglund et al., 2013a). Therefore, finding measures to prevent injury are important to increase the chance of success.

1.2 Musculoskeletal Injuries in Football

Within football, musculoskeletal injuries account for 97% of the total injuries sustained, with 87% of those injuries occurring in the lower extremities (Appendix A) (Ekstrand et al., 2011); hamstring strains are the most common of these injuries resulting in moderate and major injury severity, defined as 8-28 days and > 28 consecutive days injured in a season, respectively (Ekstrand et al., 2020; Ekstrand et al., 2011; Haggland et al., 2005). With a typical football season consisting of 38 league matches and a number of cup games between July to May, losing more than 28 consecutive days can be significant as a player may miss 4-8 matches. As mentioned in section 1.1, the consequences of having a severe injury can have major implications for the stakeholders involved; including the healthcare service that will be required to utilise resources to treat the athlete and the employer who would be affected financially depending on how key the player is and the impact of their absence upon results. The implications could also be severe for the athlete due to a loss of earnings, potential long-term health issues including disability and early retirement. In addition, the risk of a hamstring re-injury rises by 13.9 – 63.3% within the first two years of returning to play, with the associated time loss also increasing depending on the severity of the initial injury (Hagglund et al., 2006; de Visser et al., 2012). The implications and prevalence of hamstring injuries in football require the study of preventative measures. To find methods preventing and reducing the risk of a hamstring injury it is important to consider and understand the mechanisms involved.

1.3 Hamstring Musculature and Mechanisms of Injury

Hamstring strains are stretch-induced injuries, meaning that they occur when the muscle is either stretched passively or activated during a stretch, referred to as an eccentric contraction (Garrett Jr, 1996). Muscle strains typically occur when the external forces applied to a muscle exceed the force produced by the muscle itself. Eccentric contractions, in particular, are associated with high forces coupled with less active motor units (Stauber, 1989). The high eccentric forces found during sprinting mean that it is the primary mechanism of hamstring strains, accounting for 57% of all hamstring injuries (Woods et al., 2004). Sprinting plays a key role in professional football, because it has been found to be the most frequent action involved in goal situations (Faude et al., 2012). In addition, the amount of high-velocity running and sprinting, essential in elite level football, has increased over time (Bangsbo, 2014; Bush et al., 2015) (*refer to section 1.4.4 for the demands of the game*). The rise in high-velocity running and sprinting over time may explain why hamstring injuries have been increasing by 4% each year from 2001 to 2014 (Ekstrand et al., 2016). As well as highlighting the trends between sprinting and its associated injuries, these findings show the importance of the hamstring muscles during high-velocity running. The hamstring muscles play a crucial role in producing horizontal force and in energy absorption and are therefore a key muscle group when running at high velocities (Morin et al., 2015; Schache et al., 2012). The hamstrings are comprised of the biceps femoris, semimembranosus and semitendinosus muscles (Figure 1). Each muscle is involved in working to push off the ground and decelerate knee extension (Yu et al., 2008; Ono et al., 2015). These muscles are highly activated during sprinting during the early stance phase where initial contact occurs and, in particular, during the late swing phase of sprinting (Yu et al., 2008; Ono, et al., 2015) (Figure 2). During the late swing phase, the activation of the hamstrings is found to be two to three times greater than the earlier phases of sprinting (Yu et al., 2008); the hamstrings also undergo an eccentric contraction during this phase, which involves lengthening of the muscles during contraction and absorbing the mechanical work being completed (Yu et al., 2008; LaStayo et al., 2003). The biceps femoris, in particular, is highly activated during the late swing phase of sprinting, which could explain why it is the hamstring muscle most liable to be injured (Higashihara et al., 2015; Woods et al., 2004). Although sprinting is the primary mechanism of hamstring strains, there are many contributing factors that must be considered to help reduce the risk of injury, particularly those that are modifiable, as opposed to some factors that cannot be modified such as age, race or previous injury.

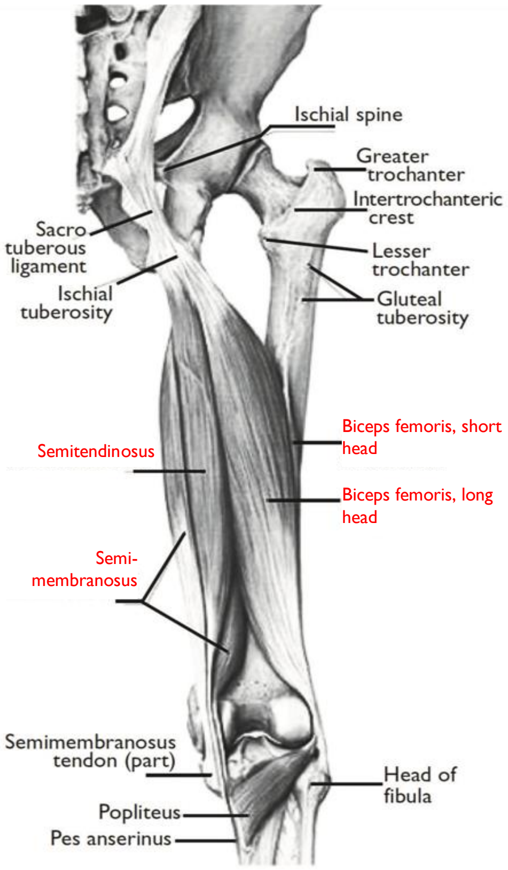

Figure 1. Rear view of the thigh showing the anatomy of the hamstring muscles (highlighted in red) (adapted from Van der Horst, 2017)

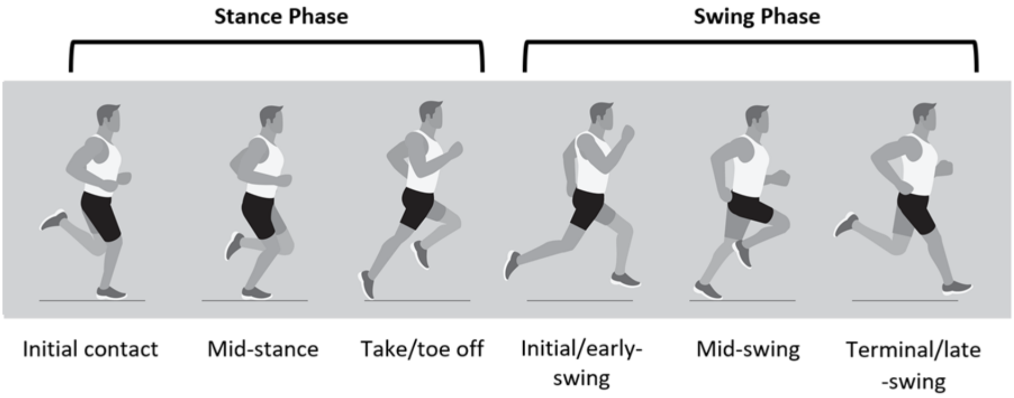

Figure 2. The phases of the Sprint Cycle (taken from Kalkhoven et al., 2020)

The modifiable factors involved in hamstring strains include shortened optimum muscle length, lack of muscle flexibility, strength imbalance between limbs, and between quadriceps and hamstring muscles, insufficient warm-up, fatigue, lower back injury, poor lumbar posture, and increased muscle neural tension (Liu et al., 2012; Lee et al., 2018).

The numerous factors influencing hamstring injury mean that the term “injury risk” can be multi-factorial and therefore extremely difficult to quantify. For this reason, many studies have isolated each factor in order to understand the effect it has on hamstring injury (Liu et al., 2012). The majority of the factors mentioned have an overall effect on ‘hamstring strength’, where reduced strength of the hamstring muscles, specifically the biceps femoris, is found to correlate with the injury occurrence during the late swing phase as the muscles are not strong enough to sufficiently contract to counteract the forces produced by the quadricep muscles (Liu et al., 2012). Additionally, it has been shown that professional football players with an eccentric hamstring peak torque weaker than 2.44 times their bodyweight and a quadriceps to hamstring ratio lower than 50.5% can increase the risk of injury 5.6-fold and 3-fold, respectively (Lee et al., 2018). In other studies, eccentric hamstring force outputs below 279 N and 337 N were found to increase the risk of hamstring injury 4.3-fold and 4.4-fold, respectively (Opar et al., 2015). Although there were many differences between the studies, the results of all concluded that improving hamstring strength is paramount to reducing the risk of hamstring injury. Therefore, it is important to consider the methods in which increased hamstring strength can be achieved in order to reduce those risks.

1.4 Training the Hamstring Muscles

1.4.1 Strength Training

Due to the predominantly eccentric nature of the hamstring muscles and high muscle activation during the late swing phase of sprinting, exercises that develop eccentric strength have been shown to be more effective in improving hamstring strength compared to concentric exercises such as the traditional hamstring curl, where the muscle shortens as opposed to lengthening when contracting (Mjølsnes et al., 2004). There are many eccentric exercises shown to illicit a high activation of the biceps femoris such as the Romanian Deadlift, Good Morning and Glute Ham Raise (McAllister et al., 2014). Additionally, while it may not isolate the muscle as much as other exercises, the Nordic Hamstring Exercise (NHE) has been found to show architectural adaptations of the biceps femoris and be effective in improving eccentric hamstring strength (Mjølsnes et al., 2004; Arnason et al., 2008; Petersen et al., 2011; Van der Horst el al., 2015; Bourne et al., 2017; Presland et al., 2018). The NHE typically involves kneeling on a pad and lowering the torso under control while the ankles are held in place by a partner or apparatus (Figure 3). In addition to being effective in improving eccentric hamstring strength, the NHE can be easily applied in the practical setting of a sports team due to its simplicity. Advancements in technology have also helped practitioners deliver the NHE using specialised apparatus'. Various hamstring testing devices such as the *Nordbord* by Vald Performance and the *Hamstring Solo* Elite by ND Sports Performance can be used to give instant feedback on the force (N) produced in the hamstring muscles of each limb. This instant feedback, displaying force output (N) and percentage imbalance between limbs, can play a crucial role in the fast-paced environment of professional sport where practitioners can act upon any significant findings by modifying the athlete's training load and providing an intervention if necessary (Gabbett et al., 2017). As mentioned in section 1.3, it is found that injury risk is 4.4 times higher when eccentric hamstring strength is below 337 N and although the evidence is mixed regarding the percentage of limb imbalance shown to increase injury risk, an aim of less than 15% between limbs is deemed to be beneficial in reducing injury risk (Bourne et al., 2015; Opar et al., 2015; Timmins et al., 2016). The feedback, when shared with the athlete, can also increase their motivation and compliance by helping them understand the reason for completing the NHE and introduces competitiveness between players, particularly if targets are set based on the research.

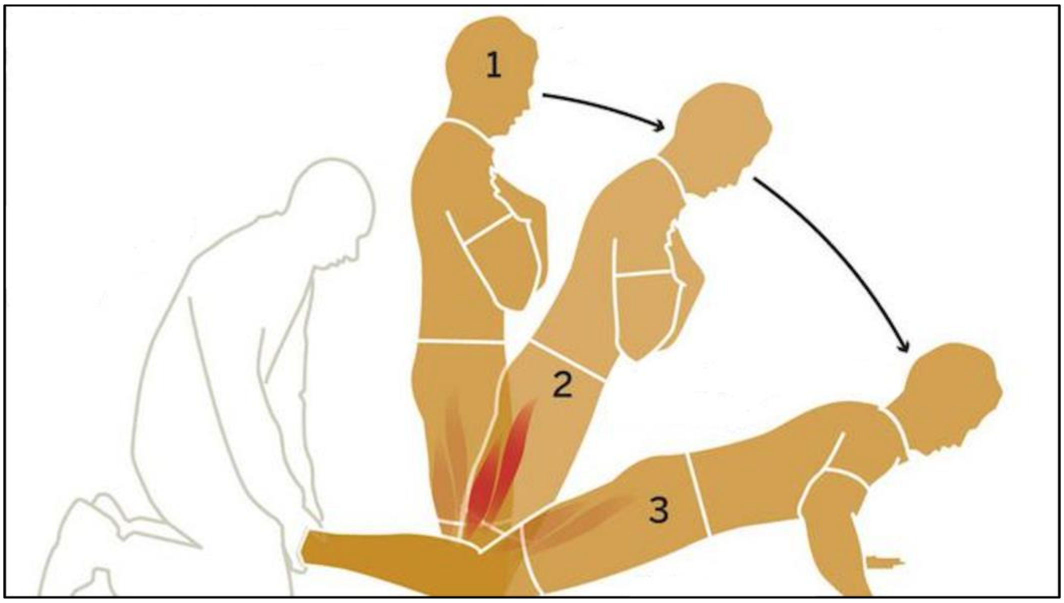

Figure 3. Performing Nordic Hamstring Exercise with a partner

The NHE involves the knee flexors to work eccentrically in order to control knee extension. This movement also occurs during the late swing phase of sprinting and has therefore been shown to be a valid measure of knee flexor strength (Chumanov et al., 2012; Opar et al., 2013). Although the NHE has been found to activate the semitendinosus muscle more than the biceps femoris, on the whole, both muscles are activated more during the NHE compared to other eccentric exercises such as the Stiff Leg Deadlift, which has a higher proportion of biceps femoris activation compared to semitendinosus (Hegyi et al., 2017). One of the benefits of the NHE is that the hamstrings contract over a large range of motion where the knee is initially flexed at 90° and extends towards 0° at the end of the movement. The peak force output during the NHE has been found to occur between 18-28° of knee flexion, where the hamstring is lengthened while contracting (Sconce et al., 2015). These angles are similar to those found during the late swing phase of sprinting, further linking the NHE to high velocity running (Higashihara et al., 2015).

1.4.2 Reliability and Validity of Hamstring Testing Devices

Since it was initially studied in the early 2000's, the NHE has become a fundamental exercise in hamstring strengthening and rehabilitation amongst strength and conditioning and medical practitioners due to its effectiveness in strengthening the hamstring muscles and reducing the risk of injury (Mjølsnes et al., 2004). As mentioned in section 1.4.1, the NordBord and Hamstring Solo Elite are two examples of specialised apparatus' manufactured due to the popularity of the NHE (Arnason et al., 2008; Opar et al., 2015; Tobin, 2017). The NordBord in particular has proved popular, where over 1,000 elite sporting teams, universities and defence departments, including more than 140 professional football teams across Europe have invested in Vald Performance's products. Since the NordBord's release, there has been a growing amount of research to show the association between the force outputs provided by the NordBord – hamstring strength and imbalance – and injury risk (Opar et al., 2015; Bourne et al., 2015). With most studies aiming to demonstrate the effectiveness of the NordBord, evidence of the reliability and validity of the equipment is limited to research on prototypes and earlier versions of the equipment (Opar et al., 2013). In the research conducted by Opar et al. (2013), the prototype NordBord showed high to moderate reliability; however, the validity of this apparatus against the other gold standard methods was not studied (Opar et al., 2013).

Currently, the use of an isokinetic dynamometer (IKD) is regarded as the gold standard method of measuring eccentric hamstring strength (Feiring et al., 1990; Aagaard et al., 1998). However, although it is regarded as the best method of measuring lower limb force output, the IKD can be difficult to incorporate within a sporting environment due to the potentially prohibitive cost of the equipment, lack of portability and the time required to conduct testing for a full squad of athletes (Whiteley et al., 2012). Conversely, the NordBord is more affordable, accessible and practical, particularly within the professional sports environment. Therefore, it is important to consider whether newer versions of the NordBord show similar reliability to their prototype versions and good validity compared to testing on the IKD.

1.4.3 Speed Exposures: Monitoring and Preparing Athletes

While the development of hamstring eccentric strength is important to reduce the risk of injury, it is also vital to stimulate the muscles by providing frequent exposures to high velocities in order to provide a training effect (Malone et al., 2017a). This may appear surprising since sprinting is the primary mechanism for hamstring injuries; however, with the nature of football relying on high velocity running it is important that players receive adequate stimulus when training to meet the demands of a competitive match. To prepare the athletes, the importance of exposing players to match situations is key, not only for tactical reasons but for physical reasons too, as the hamstring injury rate is 9 times higher during a match compared to training (Ekstrand et al., 2016). To ensure that players are prepared for the physical demands of competition, practitioners will aim to provide a consistent physical stimulus during training to avoid any sudden increases in workload, particularly those caused by matches. Infrequent or over-exposure to a stimulus is considered a ‘spike’ in an athlete’s workload, which is found to be a risk factor in injury (Gabbett et al., 2016; Colby et al., 2018). These spikes in training are shown in Gabbett et al.’s work on the acute:chronic workload ratio (ACWR), which looks into an athlete’s short-term training workload compared to their long-term workload to identify any large increases in work completed. It is important that the players are overloaded to gain a training response; however, a gradual overload is required to avoid any spikes in workload which may result in an increased risk of injury (Reilly, 2006). When analysing training load, internal and external load is considered (Halson, 2014). Internal load is the metabolic stress placed on the body, which is monitored using heart rate monitors and often the rating of perceived exertion for a session (sRPE); external load is the sum of work completed and is most commonly monitored using Global Positioning Systems (GPS) or accelerometers (Halson, 2014; Impellizerri et al., 2004).

The use of GPS has increased dramatically over the previous two decades, highlighted by the exponential growth of research relating to GPS technology released from 2001 to 2018, starting at 3 articles per year and growing to 136 articles per year (Malone et al., 2020). Over these years the technology has developed, with the addition of inertial sensors, heart rate connectivity and improved processing power all built into a much smaller device than before. The technology has also become more reliable as the devices have improved their sampling rate and satellite communication (Scott et al., 2016). In Scott’s study, a sampling rate of less than 5 Hz showed poor reliability; however, current devices with sampling rates in excess of 10 Hz (meaning that they update 10 times per second) are shown to have good reliability in tracking the movements associated with team sports. The signals received by GPS to track movements are obtained by satellites orbiting the Earth, where a minimum of four satellites are required to determine the position of the GPS receiver trigonometrically, with more than six required for improved connectivity and quality of data (Malone et al., 2017b). The physical aspects and movements most commonly analysed to measure external load in football, using GPS, are total distance covered, the speed (velocity) that distance has been covered, accelerations and decelerations, and PlayerLoad, which is an arbitrary value encompassing horizontal, lateral and vertical movements as well as the physical contact suffered during an activity (Cummins et al., 2013; Morgans et al., 2014). By using these metrics to monitor the players, practitioners have been able to identify the trends and requirements of training and matches to help them prepare for the demands of the game.

1.4.4 Demands of the Game

The typical distance covered by a top-level outfield male player during a match is 10–14 km, where 90% of the total match duration is spent standing, walking or jogging at a low intensity (Bangsbo et al., 1991; Mohr et al., 2003; Bangsbo et al., 2006; Mascio & Bradley, 2013). High intensity activities, comprising high-speed running and sprinting account for only 2.1% and 0.6% of the total duration of a match, covering a distance of approximately 460-950 m and 170-400 m, respectively (Bradley et al., 2013; Mascio & Bradley, 2013; Anderson et al., 2016). Despite high-speed running and sprinting only occurring for small periods of a match, it is found that these occasions are linked to the most significant moments of competition, such as goals scored (Di Salvo et al., 2009; Faude et al., 2012; Barnes et al., 2014). Furthermore, the distances of high-speed running and sprinting have risen by 24-36% from seasons 2006/07 to 2012/13, increasing the demands placed on the players (Bush et al., 2015).

The physical demands placed upon the players during matches can differ significantly dependent upon their playing position (Mohr et al., 2003; Domene, 2013). There can be discrepancies amongst different studies regarding their classification of playing positions and speed thresholds. However, generally it is found that central defenders cover the least total distance, high-speed running distance and sprint distance. Central midfielders are also found to cover less high-speed running and sprint distance although they cover the most total distance compared to other positions. Wide players, including both attacking and defensive positions, are found to cover high total distances and the most high-speed running and sprint distance, with strikers following a similar pattern but with less total distance (Appendix B) (Di Salvo et al., 2007; Bangsbo, 2014; Andrzejewski et al., 2015; Abbott et al., 2018). Within positions, there can be further disparity in the physical demands depending on differing circumstances within a match, for example if the team is controlling the game or having to mostly defend, and/or the style of play that is dictated by the culture of the league or managerial preference (Dellal et al., 2011). Therefore, it is important to consider training each player to cope with the physical demands placed upon them depending on their specific role in the team.

Football training predominantly involves small areas, where key emphasis is placed on small sided games (SSG's) due to their ability to mimic situations and intensities found in a match (Owen et al., 2004). However, the match situations that SSG's tend not to simulate, due to the restricted space, is the exposure to high velocity running, which as mentioned before is a key physical aspect of football. Therefore, supplementing training with linear running for players to be exposed to high velocity running may play an important role in managing the athlete's workload, avoiding spikes which can arise on the day of competition. It has been found in Gaelic and Australian Rules Football that frequent exposures to high velocity running reduce the risk of hamstring injuries (Malone et al., 2017a; Colby et al., 2018). In Malone's study it was shown that an exposure to a velocity above 95% of a players' maximum speed ($max_{>95\%}$) even once per week, in training, can lower the risk of injury, with 6-10 exposures found to be the optimal amount for reducing the risk of injury (Malone et al., 2017a). These values are relative to the physical demands of Gaelic football, where during a match, players typically complete 44 sprint actions corresponding to a higher sprint distance than football (soccer) (445 ± 169 m versus 285 ± 115 m, respectively) (Bradley et al., 2013; Mascio & Bradley, 2013; Anderson et al., 2016; Malone et al., 2016). With football showing lower sprint demands during a match, maximal efforts at $max_{>95\%}$ may need to be prescribed during training to reach the recommended dose of weekly exposures for reduced injury risk. However, within the practical setting of football, it can be difficult to achieve an exposure to a velocity above $max_{>95\%}$ due to lower motivation levels and freshness during training versus match conditions (Van de Pol & Kavussanu, 2012). Although exposures above $max_{>95\%}$ were shown to be the most effective in reducing the risk of injury, being exposed to velocities above 90% of an individual's maximum speed ($max_{>90\%}$) would be more achievable in football training and therefore may be more appropriate to use. Colby et al. found a similar trend in Australian Rules Football using 85% of a player's maximum speed ($max_{>85\%}$), showing that 5-8 efforts reduced injury risk; However, Malone et al. (2017a) did not find efforts above $max_{>85\%}$ to be as beneficial in reducing the risk of injury. Therefore, for the purpose of this study $max_{>90\%}$ was used. Since Malone et al.'s original study, looking at Gaelic football, further research has followed on football (soccer) (Malone et al., 2018). Similar to the previous study, a U-shaped trend was found, with the risk of injury increasing if values were too low or, in particular, too high. However, in this study distances were investigated rather than individual exposures, where 701-750 m of high-speed running and 201-350 m of sprint distance per week were shown to reduce injury (Malone et al., 2018). The current research shows the emerging importance of top speed exposures and distance on reducing injury risk; however, no previous studies have investigated the relationship between top speed exposures above 90% of an individual’s maximum speed and their effect on the force output of the hamstrings using the NHE in football. This study aims to fill this knowledge gap.

1.5 Objective and Aim of Study

The overall objective of the study is to focus on eccentric hamstring strength, one of the factors relating to hamstring injury risk, and determine the effects that maximal velocity running has on it. The objective is to find any relationships between these factors that could be applied within the practical setting of football in order to help prevent injuries linked to hamstring strength.

The aims of the study are to:

- Investigate the relationship between total weekly sprint distance (m) and hamstring force output when performing the NHE.
- Find the relationship between the number of exposures above 90% of maximum velocity ($\text{max}_{>90\%}$) and hamstring force output when performing the NHE.
- Determine the optimal total weekly sprint distance and number of exposures ($\text{max}_{>90\%}$) to illicit a high eccentric force output and determine the point where force begins to drop when performing the NHE.
- Determine whether total sprint meterage or the number of individual exposures above $\text{max}_{>90\%}$ has the largest effect on decreasing force output during the NHE.

In addition to the main study, two further investigations were conducted. The aim of the investigations was to determine the within/between day test-retest reliability of the NordBord and whether it is a valid method of determining eccentric hamstring strength.

1.6 Hypothesis

In order to be confident of using the NordBord for this study, test-retest reliability of the apparatus would need to show a coefficient of variation (CV) value of less than 20% and have a correlation (ρ) greater than 0.31 with the IKD during both isometric and eccentric contractions (Hopkins, 2002; Cormack et al., 2008; Opar et al., 2013).

It was hypothesised that sprint efforts above 90% of a player’s maximal velocity would be more relevant in determining the optimal eccentric hamstring force output than efforts above 95% based on the physical demands of football. Although this study is monitoring eccentric hamstring strength and not injury risk as a whole, it was hypothesised that trends would be similar to those found in previous research, with the optimal eccentric hamstring force output occurring when the players performed 200-350 m of sprint distance, which again is relevant to the physical demands of football (Bradley et al., 2013; Mascio & Bradley, 2013; Anderson et al., 2016; Malone et al., 2018). Finally, it was also hypothesised that with the demands of football being different to Gaelic football, with less sprinting required, optimal eccentric hamstring force output could be obtained with less than 6-10 efforts, as proposed by previous research (Malone et al., 2017a).

2. Methods

2.1 Participants

Fifty-eight male players from a professional football team took part in the study (Table 1). Within these subjects, 20 were measured over the course of one and a half football seasons (July 2018-January 2020), 14 were measured over the course of one full football season (July 2018-May 2019) and 24 players were measured over the course of half a football season (July-January or January-May between 2018-2020). Any players that could only be measured for less than half of a season, such as short-term loans and players with long-term injuries, were omitted from the study. Goalkeepers were also omitted from the study due to the different nature of their activity. Players were categorised as ‘defenders’, ‘midfielders’ and ‘attackers’ based on the position they played most during the duration of the study. Players who played as centre backs, full backs or wing backs were regarded as defenders. Players who played as central midfielders, whether defensive or attacking, or right and left midfielders were regarded as midfielders. Finally, players who played as strikers or wingers were regarded as attackers. The reason for grouping the players into three general positions was for simplicity and to account for any ambiguity based on slight differences in formations and roles. The participants were all full-time professional athletes, training at least three days per week, from the elite and development squads. All players played competitive fixtures at their respective age groups, including the Scottish Premier League, Reserve League and the Under 18’s League.

Table 1. Profile of participants (Mean ± SD)

Participants	Playing Positions	Age (years)	Height (cm)	Mass (kg)
n = 58	Defenders (n = 21)	21.7 ± 4.2	183.4 ± 5.7	78.9 ± 8.2
	Midfielders (n = 17)	21.5 ± 5.4	177.7 ± 5.3	71.1 ± 8.1
	Attackers (n = 20)	22.2 ± 4.6	181.3 ± 7.0	78.4 ± 10.7

Positions were determined by where the majority of playing time occurred throughout the study.

2.2 Study Design

Before the start of the study, Participants received an information sheet detailing the purpose, potential risks and benefits of the study before written informed consent was obtained. This study was approved by the NHS, Invasive or Clinical Research Committee (NICR) at the University of Stirling (18/19 -004).

The effects of maximal velocity running on eccentric hamstring strength were studied over the course of one and a half football seasons between 2018 and 2020 by monitoring two aspects of performance, the players' running load and hamstring force output (N). Running load was studied by monitoring the speeds and distances that players ran during training and matches and eccentric hamstring strength was measured when performing the NHE.

2.3 Protocol

2.3.1 Sprint Monitoring

Players' movements were monitored during training sessions and matches. Training session data was captured daily, from the start of the warm-up to the end of the session. Match data was captured from kick off to the final whistle (or the total duration of the players' involvement, if they were substituted on or off the pitch during the match). The training and match data were monitored using special Global Positioning Systems (GPS) devices designed to measure external load (*Catapult Optimeye X4, 2.4 GHz RF Device, Catapult Sports, Melbourne, Australia*). These devices had a sampling rate of 10 Hz and the velocity dwell time (minimum duration of effort) was set to 0.6s, for consistency with previous data held at the football club (Varley et al., 2017). On average, there were eight satellites connected to the devices during training and matches, suggesting that the quality of data was sufficient (Malone et al., 2017b). The GPS device was worn in a Catapult vest, specifically designed to place the GPS unit between the shoulder blades and limit device movement. It was important that the device was placed in the vest correctly, ensuring the unit was not inserted at an angle and the power button was facing the outside to improve reliability of the satellite signal and movements recorded. These data were initially downloaded and analysed on the manufacturer's software (Catapult Sport's Openfield Console and Openfield Cloud) before exporting to Microsoft Excel for further analysis. For this study, the focus was placed upon the metrics showing sprint distance (m), number of sprint efforts above 90% and 95% of the individual's maximum velocity, sprint distance above 90% and 95% of the individual's maximum velocity (m) and their maximum velocity (m/s) recorded in each session. Other than sprint distance, which was a pre-set parameter on the software, these parameters were created manually on the Openfield Cloud. These values were then combined across each day to present weekly totals. Each weekly total of the sprint data, which included all training sessions and matches, were then analysed with the corresponding NHE scores for that week.

For sessions when data were not obtainable as a result of the players not wearing or turning on the GPS unit, the unit cutting out due to battery issues or the data being unreliable due to an intermittent satellite signal, estimations were used. For training data, these estimations were taken, as an average, from the other players of a similar position who completed the same drills within the session. For match data, these estimations were taken, as an average, from the individual's previous five matches (Bowen et al., 2017).

2.3.2 Nordic Hamstring Exercise

The players were required to perform one set of three repetitions of the NHE per week. These were primarily performed two days after a match (MD+2) as part of the players' strength and conditioning programme. The strength and conditioning sessions were completed in the morning before training, with the NHE being the first exercise in the programme to avoid being in a fatigued state when performing the NHE so that optimal scores could be obtained. As it was the first exercise, the players were required to perform one set of three repetitions of the NHE at 50% effort as a warm up, followed by one set of three repetitions at maximal effort. Each repetition was performed on a hamstring testing device specifically designed for performing the NHE (*NordBord Hamstring Testing System, 50 Hz, Vald Performance, Queensland, Australia)* (Figure 4), which was used to measure each leg's force output (N) and between limb strength imbalances during the lowering eccentric phase of the NHE. The exercise was recorded on a windows laptop or iOS device using the manufacturer's live software (ScoreBord) (Figure 5) and then uploaded to the manufacturer's online platform (Dashboard), where it was then exported to Microsoft Excel for further analysis. Specifically for the purpose of the study, each player's weekly peak force (N) scores were analysed alongside the sprint data for that corresponding week.

Figure 4. NordBord Hamstring Testing System, Vald Performance

Figure 5. Trace of NHE on Vald Performance's ScoreBord software

The protocol of the NHE involved the player to place their heels under the hooks with their knees placed on the NordBord. Their knee position was recorded in the software for consistency during every repetition each time the exercise was performed (Figure 6 – *Scan QR Code for how knee position was determined*). For the starting position the player's knees began at 90°. Once in position, the player was then required to lower their torso in a controlled manner over a minimum of three seconds, until they could no longer hold the movement. During this movement the players were encouraged to keep their shoulders, hips and knees in line through verbal cues given by the practitioner so that neutral hip alignment was maintained. They would then catch themselves at the end of the movement by placing their hands on the floor, walk their hands back in and, when ready, repeat to complete three repetitions (Figures 7 & 8). The players were allowed a maximum of three minutes to complete all three repetitions, with most players requiring less than one minute.

Figure 6. How to select a NordBord knee position

Figure 7. Performing the Nordic Hamstring Exercise on NordBord. (A) Starting in upright position, (B) contracting knee flexors during movement to control descent, (C) finishing by placing hands on ground after breaking point; all while ankles are secured by hooks attached to load cells.

Figure 8. Video showing how to perform Nordic Hamstring Exercise on NordBord

As discussed in section 4.2, for validity purposes the NHE can require a thorough familiarisation period due to the complexity of the exercise. Therefore, the players' data were only recorded once they had completed a minimum of three weeks of the exercise protocol; However, many of the players had previous experience of using the NordBord so their data were recorded from the beginning. When it was impossible to test a player's NHE due to scheduling issues, managing the player's training load or for any other reason, that corresponding week was removed from the analysis.

2.4 Statistical Analysis

All data were initially exported to Microsoft Excel for the first stage of analysis. At this stage, the data were sorted and filtered based on the criteria mentioned above. The percentage change in eccentric hamstring strength was calculated for each player to account for their individual differences. Each player's percentage change in strength was calculated using the mean value of the first three NHE tests to illicit a coefficient of variation of <10% (*refer to chapter 3.3*). Further analysis was then completed on SPSS Statistics Version 26 (IBM Corporation, New York, USA). A correlation coefficient analysis using Spearman's rho was used to measure the degree of association between total weekly sprint distance (m), efforts above 90% and 95% of each player's maximum velocity and their effect on eccentric hamstring strength; correlations with a $P < 0.05$ were deemed as significant. A correlation (ρ) less than 0.30 was considered small; 0.31 to 0.49 moderate; 0.5 to 0.69 large; 0.70 to 0.89 very large; and 0.90 and higher near perfect (Hopkins, 2002). These thresholds also applied to negative values indicating a negative correlation. A one-way ANOVA with Tukey's post hoc test was used to determine any significant differences between the total weekly sprint distance, efforts > 90% and efforts > 95% on the mean percentage change in eccentric hamstring force.

2.5 Reliability of NordBord

To investigate the reliability of the NordBord, seven physically active male participants (Mean ± SD, age: 26 ± 2 years; height: 181 ± 8 cm; mass: 82 ± 9 kg), who were separate to the original cohort used in the main study, were asked to complete one set of three repetitions of the NHE on the NordBord (Test 1). They were then asked to repeat the protocol on the same day (Test 2, intra-day) and again after exactly one week (Test 3, inter-day) (*see chapter 2.3.2 for protocol*). Between completing Test 1 and Test 2, each participant was given approximately fifteen minutes of rest before re-testing. This timescale ensured that the participants received adequate recovery time without having to re-warm the hamstring muscles (Silva et al., 2018).

All NHE data were extracted from Vald Performance's "Dashboard" to Microsoft Excel and the greatest values for each test were used for further analysis. Intra and inter-day coefficient of variation (CV) and intraclass correlation coefficient (ICC) were calculated using combined mean peak force (N) and standard deviation of both limbs obtained from the NHE during Test 1 and Test 2, and Test 1 and Test 3, respectively. A CV of 10% or lower was deemed to show good reliability, 10-20% average reliability and >20% to show poor reliability (Cormack et al., 2008; Opar et al., 2013). ICC values of 0.90 or greater were regarded as high, between 0.80 and 0.89 as moderate, and 0.79 or less as poor (Wiesinger et al., 2020).

2.6 Validity of NordBord

To investigate the validity of the NordBord, six physically active male participants (Mean ± SD, age: 29 ± 2 years; height: 178 ± 5 cm; mass: 78 ± 8 kg), who were separate to the original cohort used in the main study, were asked to complete one set of two repetitions of an isometric contraction on each lower limb with 60° knee flexion (Test 1) and one set of three repetitions of the NHE (Test 2), both on the NordBord. This was followed by one set of two isometric contractions at 60° (Test 3) and one set of three eccentric contractions at 60°/s (Test 4), starting from a knee angle of 90° and finishing with full knee extension, on the IKD (*Kin Com, Chattanooga, Hixson, TN, USA*). This gave a measurement of isometric and eccentric hamstring force output from the NordBord and IKD, respectively. Before Test 1, each participant performed a two-minute continuous cycle on a static bike to warm up and approximately fifteen minutes of rest were given to each individual before moving on to the next test. Test 1 involved the participant placing their ankles within the hooks and knees placed in the relevant position similar to the NHE. However, on this occasion the participant was required to place their hands on the floor in a prone position to illicit 60° knee flexion, measured by a goniometer. This position was maintained throughout the full isometric test on the NordBord. Once in position, the participant was required to pull one limb with maximal exertion, while maintaining 60° knee flexion, for five seconds. On completion, ten seconds of rest was given, and was then repeated with the other limb to complete one repetition. Test 2 was completed exactly as described in section 2.3.2 *Protocol of Nordic Hamstring Exercise*. When testing on the IKD (Tests 3 and 4), no warm up was required due to completion of previous tests on the NordBord. The participants were securely fixed to the IKD using the straps provided and were instructed to perform a maximal contraction to counteract the force produced by the device. Once strapped in, both isometric and eccentric peak force values were recorded for each participant on the IKD's built-in software.

All isometric and eccentric data recorded on the NordBord and IKD were exported from Vald Performance's "Dashboard" and the IKD, respectively, into Microsoft Excel for further analysis. Peak force (N) of each lower limb and combined right and left limbs from the isometric and eccentric tests on both devices were analysed by a regression model using Pearson's correlation coefficient to determine the strength of the relationship; correlations with a $P < 0.05$ were deemed as significant. A correlation (r) less than 0.30 was considered small; 0.31 to 0.49 moderate; 0.5 to 0.69 large; 0.70 to 0.89 very large; and 0.90 and higher near perfect (Hopkins, 2002). The coefficient of determination (R^2) was used to predict the proportion of inter-participant variance in force (N) between NordBord and IKD.

3. Results

3.1 Participant Data

The mean maximum velocity of the 58 players was 9.27 ± 0.27 m/s. In addition, per week the players covered an average of 212.1 ± 188.6 m, 0.96 ± 1.39 efforts >90% of maximum velocity and 0.02 ± 0.14 efforts above 95% of maximum velocity (Table 2). Refer to Table 2 for a breakdown of the players' sprinting profile based on their playing positions. Over the course of the study, the players sprinted 209,139 m. In addition, 947 efforts above 90% of maximum velocity were recorded but only 16 efforts above 95%. As the number of efforts recorded above 95% of maximum velocity were so low, any additional findings regarding efforts >95% are tentative.

Table 2. Sprinting profile of players using GPS data. Data are presented based on the players' playing positions and as a collective group (Mean ± SD)

Position	**Maximum Velocity (m/s)**	**Weekly Sprint Distance (m)**	**Weekly efforts >90% of Max Velocity (n)**	**Weekly efforts >95% of Max Velocity (n)**
Defenders	9.30 ± 0.24	204.8 ± 178.8	1.12 ± 1.51	0.02 ± 0.14
Midfielders	9.19 ± 0.23	208.4 ± 193.2	0.86 ± 1.24	0.01 ± 0.10
Attackers	9.32 ± 0.30	224.7 ± 195.3	0.87 ± 1.37	0.02 ± 0.18
Overall Squad	9.27 ± 0.27	212.1 ± 188.6	0.96 ± 1.39	0.02 ± 0.14

The overall squad of players produced a mean hamstring force output of 427.47 ± 57.98 N with a mean strength imbalance of 8.20 ± 6.65% between limbs (Table 3). Refer to Table 3 for a breakdown of the players' hamstring strength and imbalances based on their playing positions.

Table 3. Hamstring strength profile of players using NordBord data. Data are presented based on the players' playing positions and as a collective group (Mean ± SD)

Position	Hamstring Strength (N)	Strength Imbalance (%)
Defenders	420.14 ± 52.84	7.90 ± 7.35
Midfielders	416.15 ± 48.80	9.87 ± 6.32
Attackers	446.98 ± 66.42	6.99 ± 5.75
Overall Squad	427.47 ± 57.98	8.20 ± 6.65

3.2 Relationship Between Sprinting and Hamstring Strength

There was a significant inverse relationship between total weekly sprint distance and the percentage change in eccentric hamstring strength, with a very small correlation shown ($\rho = -0.13$, $P < 0.01$) (Table 4). There was also a significant inverse relationship between the total weekly efforts above 90% of maximum velocity and the percentage change in eccentric hamstring strength, again with a very small correlation shown ($\rho = -0.08$, $P = 0.01$).

Total weekly efforts above 95% of maximum velocity showed no relationship with the percentage change in eccentric hamstring strength ($\rho = -0.02$, $P = 0.45$).

Table 4. Spearman correlation (ρ) between percentage change in eccentric hamstring force compared with weekly sprint distance (m), weekly efforts >90% of maximum velocity and weekly efforts >95% of maximum velocity

	Sprint Distance	Efforts >90% of Max Velocity	Efforts >95% of Max Velocity
Percentage Change in Hamstring Force	-0.126**	-0.082**	-0.024

***. correlation is significant at the 0.01 level (2-tailed)*

The mean percentage change in eccentric hamstring force was not significantly influenced by weekly sprint distance, $F_{(940, 58)} = 0.93$, $P = 0.66$. As no apparent trend was shown between these factors, the optimal total weekly sprint distance could not be determined (Figure 9).

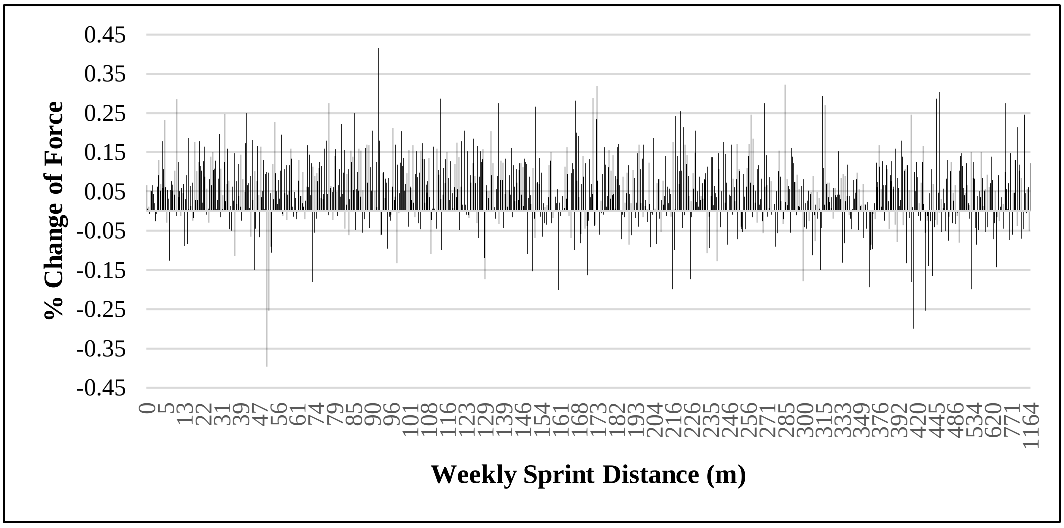

Figure 9. The mean percentage change in eccentric hamstring force in relation to total weekly sprint distance (m)

The mean percentage change in eccentric hamstring force was significantly influenced by weekly efforts >90% of maximum velocity, $F_{(3, 58)} = 3.71$, $P = 0.01$. Post hoc analysis using Tukey's method showed that these significant differences in the mean percentage change in eccentric hamstring force occurred when comparing 0-2 and 5-6 sprint efforts with 7-8 efforts; the differences were 0.11% ($P = 0.03$) and 0.12% ($P = 0.03$), respectively (Figure 10).

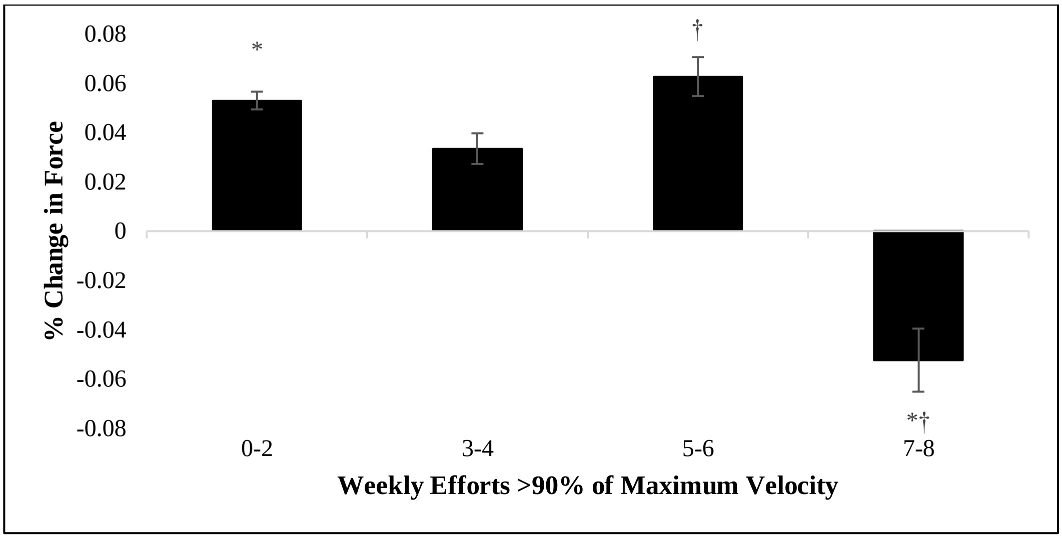

Figure 10. The mean percentage change in eccentric hamstring force in relation to weekly sprint efforts >90% of maximum velocity (denotes significance between 0-2 and 7-8 efforts; † denotes significance between 5-6 and 7-8 efforts, P<0.05)*

3.3 Reliability and Validity of NordBord

The seven participants of the reliability study had a mean NHE score of 390.61 ± 39.22 N and a CV value of 10% suggesting good reliability when performing the NHE on the NordBord during the intra-day testing. During inter-day testing the mean NHE score was not significantly different (399.60 ± 43.85 N, P = 0.068), with a CV value of 11% to show average reliability. ICC values were 0.80 [95% CI: 0.21, 0.96] for intra-day testing and 0.95 (95% CI: 0.74, 0.99] for inter-day, indicating moderate and high correlations, respectively. Each participant's eccentric hamstring strength scores during intra-day and inter-day testing are shown in Table 5.

Table 5. Average of right and left limb eccentric hamstring strength of each participant during intra-day (Tests 1 & 2) and inter-day (Tests 1 & 3) reliability of the NordBord

Participant	**Test 1 (N)**	**Test 2 (N)**	**Test 3 (N)**
1	403	403	416
2	429	421	443
3	366	375	368
4	417	412	438
5	380	390	396
6	444	382	436
7	334	317	327
Mean ± SD (N)	396 ± 38	385 ± 34	403 ± 43

With isometric testing on the IKD, mean maximum force outputs were 349.50 ± 47.65 N and 287.17 ± 48.75 N in the left and right hamstring, respectively. For both limbs combined, a mean IKD score of 318.33 ± 40.94 N was found. Mean maximum force outputs were higher with isometric testing on the NordBord with outputs of 448.67 ± 80.00 N on the left hamstring, 478.83 ± 72.89 N on the right hamstring and a mean of 463.75 ± 68.16 N when averaging both limbs. Small correlations were found between the IKD and NordBord when testing hamstring isometric strength on the left, right and both limbs, respectively (r = -0.074, 0.147, -0.047) (Table 6a).

Table 6a. Descriptive statistics of isometric hamstring strength testing on IKD and NordBord for validity (n = 6)

	Left Limb		Right Limb		Both Limbs	
	IKD Max Force (N)	NordBord Max Force (N)	IKD Max Force (N)	NordBord Max Force (N)	IKD Max Force (N)	NordBord Max Force (N)
Mean ± SD	349.50 ± 47.65	448.67 ± 80.00	287.17 ± 48.75	478.83 ± 72.89	318.33 ± 40.94	463.75 ± 68.16
r	-0.074		0.147		-0.047	
R²	0.005		0.022		0.002	
P-value	0.053		0.002		0.007	

The mean maximum force output of the hamstring increased when testing eccentrically on the IKD with 489.72 ± 97.48 N, 425.92 ± 95.93 N and 457.82 ± 86.28 N of force produced in the left limb, right limb and both limbs, respectively. In contrast, eccentric testing on the NordBord displayed a lower mean maximum force output compared to isometric testing with 354.67 ± 76.38 N of force produced by the left hamstring, 371.50 ± 77.60 N on the right hamstring and a mean of 363.08 ± 75.68 N when averaging both limbs. A moderate correlation was found between the IKD and NordBord when testing hamstring eccentric strength on the right limb (r = 0.444), with large correlations found on the left limb (r = 0.530, P = 0.017) and both limbs combined (r = 0.528, P = 0.044) (Table 6b; Figures 11a & 11b).

Table 6b. Descriptive statistics of eccentric hamstring strength testing on IKD and NordBord for validity (n = 6)

	Left Limb		Right Limb		Both Limbs	
	IKD Max Force (N)	NordBord Max Force (N)	IKD Max Force (N)	NordBord Max Force (N)	IKD Max Force (N)	NordBord Max Force (N)
Mean ± SD	489.72 ± 97.48	354.67 ± 76.38	425.92 ± 95.93	371.50 ± 77.60	457.82 ± 86.28	363.08 ± 75.68
r	0.530		0.444		0.528	
R^2	0.281		0.197		0.279	
P-value	0.017		0.247		0.044	

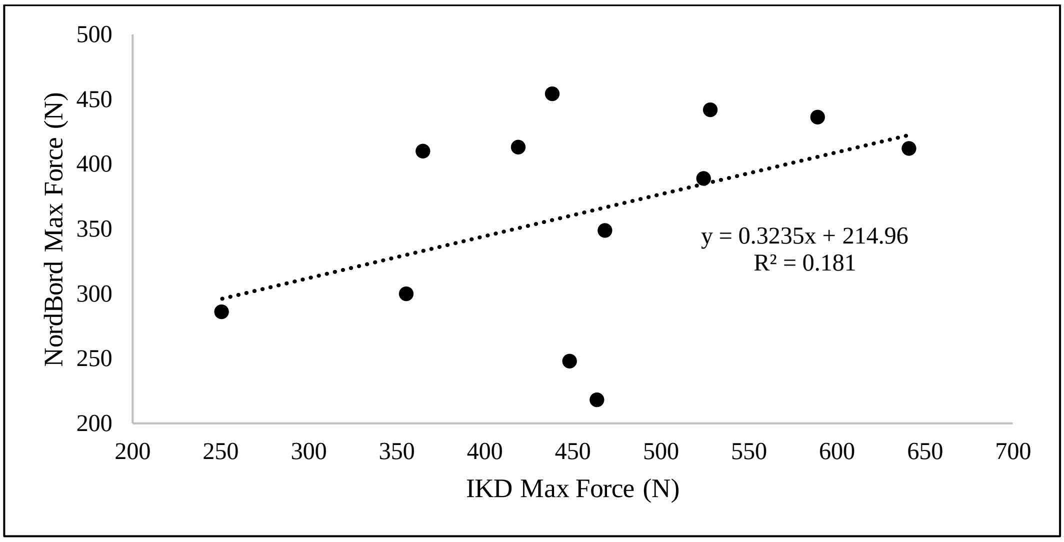

Figure 11a. Maximum eccentric force (N) of left and right limb combined; IKD vs NordBord

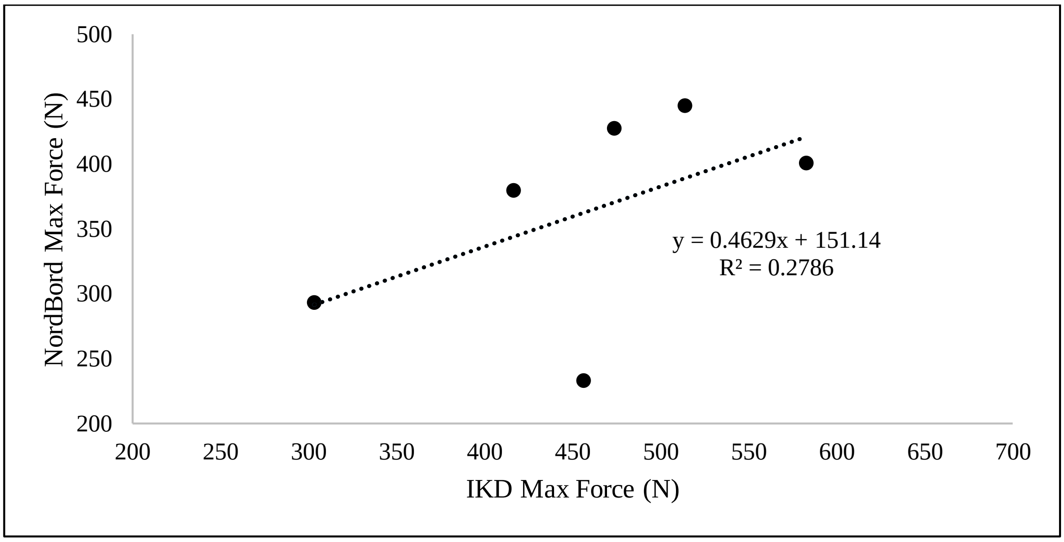

Figure 11b. Maximum eccentric force (N), mean of left and right limb; IKD vs NordBord

4. Discussion

4.1 Main Findings

The aims of this study were to investigate the influence of total weekly sprint loads performed during training and matches. Using the information gained during this investigation, the aim was then to establish the optimal values required to illicit a high eccentric force output and determine which of the factors studied had the largest influence on hamstring strength. Although previous studies have investigated the effects of maximal efforts and sprint volume on injury risk, to the best of our knowledge this is the first study to investigate the relationship between maximal efforts and sprint volume on a single factor of injury risk – eccentric hamstring strength. Prior to these findings it was important to determine the within/between day test-retest reliability of the NordBord and whether it is a valid method of determining eccentric hamstring strength.

Performing the NHE on the NordBord showed good to average test-retest reliability and was found to be a valid method of measuring eccentric hamstring strength. Measuring isometric hamstring strength on the NordBord did not show a significant correlation with IKD testing. The main findings of this study were that eccentric hamstring strength levels significantly decreased when 7-8 weekly efforts at $\text{max}_{>90\%}$ were completed but not at 0-6 weekly efforts (Figure 10). Total weekly sprint distance or the weekly number of efforts completed at $\text{max}_{>95\%}$ were found to have no influence on eccentric hamstring strength. The number of maximal efforts and sprint distance required to illicit optimal levels of eccentric hamstring strength in professional football players could not be determined; however, the study was able to establish the limit of weekly exposures at $\text{max}_{>90\%}$ before a decrease in hamstring force output occurs.

4.2 Reliability and Validity

The findings of this study seem to follow similar trends with studies on the reliability of eccentric hamstring measuring devices. Like this study, previous studies using prototype versions of the NordBord also found good to average reliability when performing the NHE (Opar et al., 2013).

Although a coefficient of variation of 11% is just outside the threshold for reliability to be deemed good, ICC values of 0.95 during inter-day testing suggest that there was a high similarity in performance between the participants (Wiesinger et al., 2020). Similar ICC results have also been found in recent test-retest studies involving an alternative eccentric hamstring measuring device, where ICC values of 0.91 were found (Lodge et al., 2020). The CV% in this study showed good to average reliability; however, it was slightly higher than that found by Opar et al. (2013) – 5.8% to 8.5%. The larger variation found in this study may be explained by the heterogeneity of the sample group compared to the previous studies, which used a more homogenous group of sub-elite athletes and/or subjects of similar activity levels; moreover, in this study there was varying experience of performing the NHE amongst participants (Opar et al., 2013; Lodge et al., 2020). Unfortunately, it was not possible to recruit the same elite athletes that were used in the main study for the reliability study because the latter required an intervention of completing back to back sets of the NHE. The additional stimulus would have been above the prescribed training programme and would have therefore affected the athlete's training week and match preparation by increasing their physical workload and fatigue levels. It has been previously shown that training experience can influence reliability of strength testing, where untrained individuals can benefit from larger training effects during initial sessions compared to trained individuals, likely due to neural adaptations and improvement of technique (Ritti-Dias et al., 2011). These large improvements obtained by untrained individuals would suggest that in future, it would be beneficial to recruit participants with similar NHE training experience or include a thorough familiarisation period of at least 2-3 sessions to account for any differences between subjects (Ritti-Dias et al., 2011); however, in relation to the main study these findings would suggest that reliability would likely improve, or at the very least be similar within a professional cohort.

When investigating the validity, higher isometric forces in the hamstring muscles were found on the NordBord compared to the IKD but force outputs were reversed when testing eccentrically, with the IKD showing greater peak force than the NordBord. The higher isometric forces produced on the NordBord in this study were unexpected considering that participants were strapped on the IKD but not on the NordBord; previous research has shown that being strapped during isometric testing elicits a higher force output produced by the lower limbs (Otten et al., 2013). However, remaining unstrapped while testing on the NordBord allows the recruitment and influence of other muscles, predominantly the gluteal muscles, thereby producing more isometric force (Read et al., 2019). The higher isometric testing values on the NordBord also contradict the understanding that hamstring peak force values are influenced by hip position, where values are found to be significantly lower in the supine or prone position than in the seated position (Worrell et al., 1981). The higher force values found in the seated position are understood to be due to the hamstring muscle being in a shortened position of hip flexion when supine or prone, whereas in the seated position the hamstring muscles are lengthened resulting in greater force production (Lunnen et al., 1981).

The factors discussed above may, however, partly explain the greater strength output found on the IKD when testing eccentrically. Additionally, force output on the NordBord may have been lower during eccentric testing because of the added complexity of the NHE and the participants' limited experience of completing the exercise. Although the participants were familiarised with the NHE on the NordBord during the study, the difficulty of the exercise can require multiple attempts and a level of training before showing complete competency, which the participants were not exposed to (Šarabon et al., 2019). For future studies, including a thorough familiarisation period with multiple sessions before commencing the study or using well-trained and accustomed individuals may be beneficial.

Although the findings of peak force output are contradictory to those found in other studies looking at the validity of the IKD and a similar hamstring measuring device (Lodge et al., 2020), importantly for the purpose of the main study, a large to moderate correlation was found between the IKD and NordBord when testing eccentric hamstring strength ($r = 0.444, 0.528, 0.530$). These correlations show that performing the NHE on the NordBord is a valid method of measuring peak hamstring force output.

4.3 Weekly Efforts at 90% of Maximum Velocity

In the professional football environment, an association between the number of weekly sprint exposures at $\text{max}_{>90\%}$ and eccentric hamstring strength was found. The most interesting finding was that when completing 7-8 efforts per week at $\text{max}_{>90\%}$, that amount of efforts had a significant negative impact on eccentric hamstring strength. These findings differ from previous studies investigating the effects of sub-maximal sprint efforts on injury risk, which have found that higher amounts of weekly maximal efforts are required before detrimental consequences occur (Malone et al., 2017a; Colby et al., 2018). These differences are likely because this study isolates and investigates one injury risk factor (eccentric hamstring strength), whereas, Malone et al. (2017a) and Colby et al. (2018) look at “injury risk” as a whole, which can be multi-factorial and therefore difficult to quantify. With these previous research articles looking at multiple injury risk factors and encompassing all injuries it may be expected that they would find that less efforts would be required to have a negative impact on injury risk, however, that is not the case. Therefore, there must be another factor to consider to explain the different findings between these studies. One of the main differences between this study and the previous studies mentioned is that each study looks into a different sport. For this study, football players were monitored, in the study by Malone et al. (2017a) they analysed Gaelic football players and the study by Colby et al. (2018) involved Australian Rules football. These three sports all differ with regards to their physical demands. In general, Gaelic football is found to have the highest sprinting demands out of the three sports, where players are found to complete approximately 44 sprint actions in a match (Malone et al., 2016). The sprinting demands of Australian Rules football are found to be similar to football (soccer), with approximately 29 and 17-36 sprint actions completed in a match, respectively (Coutts et al., 2010; Di Salvo et al., 2010; Schimpchen et al., 2016). Although the total number of sprint actions is similar, it is found in football that players complete the majority of sprints over 0-10 metres and only complete an average of 0.9-2.2 sprint efforts for distances greater than 20 metres, whereas, higher sprint distances are found in Australian Rules football, likely due to the influence of the larger pitch dimensions found in the sport (Fleay et al., 2018; Castillo et al., 2021). The low number of sprints completed in a football match at distances greater than 20 metres may explain why no more than 8 efforts per week at $\max_{>90\%}$ were recorded in this study, as it is at these greater distances that higher speeds are typically achieved. Additionally, in this study the players were found to complete, on average, approximately one effort per week, therefore based on the ACWR it is of no surprise that eccentric hamstring force drops once a player has completed 7-8 efforts as these values are not being achieved on a regular basis to build up a tolerance to the chronic workload (Gabbett et al., 2016). This observation is important for practitioners working in football to monitor the players' weekly sprint efforts at $\max_{>90\%}$, particularly in conjunction with each athlete's ACWR.

4.4 Weekly Efforts at 95% of Maximum Velocity

It was observed in this study that football players completed only 14 efforts at $\max_{>95\%}$ over the course of one and a half playing seasons, corresponding to an average of 0.02 efforts per week. Therefore, due to such a low number of occurrences no relationship was found between efforts at $\max_{>95\%}$ and eccentric hamstring strength. This supports the hypothesis suggesting that monitoring efforts at $\max_{>95\%}$ may not be applicable in the practical setting and that using $\max_{>90\%}$ would be more appropriate based on the physical demands of football during training and matches. Studies monitoring sprint efforts based on a percentage of a player's maximal velocity in football are very limited; However, in Gaelic football it is found that players completed an average of 7 ± 4 efforts at $\max_{>95\%}$ in a week, with an average of 4 efforts completed during training and 3 efforts during matches (Malone et al., 2017a). This is significantly higher than the results found in this study, which as mentioned in section 4.3, are likely attributed to the higher sprint demands of Gaelic football.

The low number of efforts at $\max_{>95\%}$ found in this study would suggest that it is very rare for football players to achieve such velocities; however, these findings may also be influenced by the GPS devices recording the data. It may be that the players reach the required velocity to obtain an effort at $\max_{>95\%}$, but these efforts may not be recorded by the GPS because the velocity is only reached for a split second. With the default dwell time being set at 0.6s this means that any occasions where the player reached an effort at $\max_{>95\%}$ for less than 0.6s would not be recorded. Additionally, although GPS devices with a 10 Hz sample rate are shown to have good reliability at measuring velocity, it is found that the accuracy of the GPS devices can decrease at higher velocities when coupled with changes of direction, which would be applicable to team sports such as football and can affect the efforts recorded (Scott et al., 2016). With changes of direction playing an important role during matches and, in particular, small-sided games during training, this may explain why very few sprint efforts per week are recorded in football. Straight-line sprinting plays a crucial role in match play, highlighting why it is important to supplement training with linear sprinting drills (Faude et al., 2012). Therefore, it may be beneficial for practitioners to develop linear sprinting drills that also incorporate the technical and/or tactical aspects of the sport, which would increase training efficiency and also help to increase player motivation and effort (Little, 2009). However, with the accuracy of the data being questioned at velocities corresponding to $\text{max}_{>95\%}$, the findings of this study further highlight that monitoring efforts at $\text{max}_{>90\%}$ are more appropriate in football and other sports involving high velocity running and changes of direction.

4.5 Weekly Sprint Distance

In this study, weekly sprint distances were not shown to influence eccentric hamstring strength. This finding was surprising considering the consistency of the data collected but may be explained by a number of reasons. To the best of our knowledge, no other study has investigated the relationship between weekly sprint distance and eccentric hamstring strength; However, a previous study has researched the effects of weekly sprint distance, in football, in relation to injury risk as a whole (Malone et al., 2018). In the study by Malone et al. (2018), trends were found between the amount of weekly sprint distance completed and injury risk; However, the study did not specify the associated injury sites. With this study solely focussing on eccentric hamstring strength, it may be that the effects of weekly sprint distance on hamstring strength are not significant enough to concur any relationship between the two factors and a significant relationship can only be found once all injury sites are included. Alternatively, there could be a similar relationship between weekly sprint distance and eccentric hamstring strength as there is with “injury risk” but the different findings in our studies may be due to other factors. In the study by Malone et al. (2018), the trends between weekly sprint distance and injury risk were only apparent when considered independently of aerobic fitness and previous training load, but these factors play an important role in the risk of injury. This may be another reason why no trends were found between weekly sprint distance and eccentric hamstring strength in this study as these factors were not considered independently of training load and aerobic fitness. Training load, in particular, seems to have a large impact on “injury risk”; it has been shown in previous studies that it was not necessarily weekly sprint distance that increased injury risk but actually rapid increases in acute workload in relation to the chronic workload (Duhig et al., 2016; Malone et al., 2018). These findings are highlighted in many other studies, which suggest that injury risk is also greatly affected by other external load measures such as total distance, low intensity distance (<4 m/s), the number of accelerations and number of decelerations (Hulin et al., 2016; Bowen et al., 2017; Murray et al., 2017; Cummins et al., 2019; Bowen et al., 2020). Therefore, it is likely that any relationships between weekly sprint distance and “injury risk” are due to ‘spikes’ in external load based on the ACWR rather than decreases in eccentric hamstring strength.

4.6 Sprinting and Hamstring Strength Trends in Football

The players in this study were shown to have an average maximum velocity of 9.27 ± 0.27 m/s and average weekly sprint distance of 212.1 ± 188.6 m. The maximum velocities of the players in this study were found to be lower than those in previous studies involving players in the English Premier League (9.55 m/s) and German national level (9.36 m/s) (Barnes et al., 2014; Schimpchen et al., 2016). The lower velocities found in this study are possibly due to the higher level of standard associated with English Premier League and International players, with elite Norwegian players shown to have similar maximum velocities (9.2 m/s) as the players in this study, arguably because the standard of football is similar in the Scottish and Norwegian Leagues (Haugen et al., 2020). Other studies have also suggested that higher maximal velocities and speed performances are associated with a greater playing level, where national and elite level players tend to out-perform sub-elite and recreational players; however, there are also some studies suggesting that sprint performance is not indicative of playing level, where these differences only occur during adolescence and are not apparent once the players reach senior level (Cometti et al., 2001; Gissis et al., 2006; le Gall et al., 2010; Slimani & Nikolaidis, 2017; Devismes et al., 2021). Therefore, within teams of a greater standard or with higher maximum velocities, careful monitoring and planning of training may be required to ensure that players are still managing to complete efforts at $\text{max}_{>90\%}$. Although research is limited in providing weekly sprint distances that incorporate training and match data, the weekly sprint distance found in this study (212.1 ± 188.6 m) was lower than previously reported for English Premier League players (a weekly average of 298 m) (Anderson et al., 2016). There are a number of factors that can affect the physical output during training and matches, which would likely account for the differences found between this study and the study by Anderson et al. (2016). There can be different demands placed on the players during training and matches dependent on preferences of the manager and coaching staff. The manager and coaching staff may also have varying tactical preferences which manipulate the style of play and physical output, where a counter-attacking team may show higher sprint performances compared to a possession-based team due to the quick transitional play associated with the former’s tactical roles. Additionally, the standard of quality between the team and their opposition during a match has been shown to affect the high-intensity and sprint distance, with successful teams having to cover less sprint distance as the quality of the opposition decreases (Miñano-Espin et al., 2017). However, a large gulf in quality can also have an effect on the inferior opposition's movements, where if they are forced to play the majority of the match in their own half of the pitch then they may not have many opportunities to sprint (Dellal et al., 2011). As there are many factors that can influence the physical output produced by a team, it may be important for practitioners to contextualise the results from this study and adjust their prescriptions based on the traits of the players/team that is being observed.

When examining positional differences, it was found that attackers were the quickest position group and covered the most sprint distance per week, with defenders covering the least. These findings are in line with many previous studies looking into the typical sprint distances during match-play, where attackers were found to cover the most sprint distance and central defenders the least in a variety of leagues, irrespective of the cultural differences in their style of play (Di Salvo et al., 2009; Dellal et al., 2010; Dellal et al., 2011). Although these studies did not include sprint distances during training, it is found that the majority of weekly sprint distance is obtained during a match and therefore has a large contribution to the weekly total (Anderson et al., 2016). Additionally, in these previous studies, fullbacks/wide defenders were found to cover high sprint distances, making it unusual that the "defenders" group in this study, consisting of central and wide defenders, would still have the lowest average sprint distance between all positional groups. This finding would suggest that either the central defenders had such low values that even the contribution of the fullbacks could not place them ahead of midfielders, who typically cover lower sprint distances than wide defenders. Or, this could also be due to the playing style of the football team, where fullbacks may not have been able to sprint as much based on the circumstances of the game and/or tactical responsibilities (Dellal et al., 2011). The addition of the fullbacks into the "defenders" positional group did however seem to have an effect on the maximum velocities across the three positions, with defenders producing a higher average maximum velocity than the midfielders. With attackers shown to have the highest sprinting demands of the three positional groups, it may be expected that they are the most likely to obtain a hamstring injury, but this is not the case, with no clear trend found within outfield players based on their position (Hagglund et al., 2013b). Attackers, however, have been found to be more susceptible to a recurrent hamstring injury, with previous injury proven to be one of the largest contributing factors of re-injury (Arnason et al., 2004; Engebretsen et al., 2010 Carling et al., 2011). The risk of re-injury in attackers is likely due the structural integrity and strength of the hamstring muscles being compromised due to previous injury and therefore being affected by the high sprint demands of the position (Schuermans et al., 2016). This suggests that hamstring strength plays a key role in reducing the risk of injury in football players, particularly for attackers.

It was found in this study that the players had an overall average eccentric hamstring force output of 427.47 ± 57.98 N and an average imbalance of 8.2 ± 6.65 %. These findings are better than the recommended level, which suggest that strength greater than 337 N and a between limb imbalance less than 15% can reduce the risk of hamstring injury risk (Bourne et al., 2015; Timmins et al., 2016). Hamstring strength, more so than limb imbalance, has been shown to have a greater influence on injury risk (Opar et al., 2015). The manufacturer of the NordBord, *Vald Performance*, has presented the distribution of results for over 21,000 NHE tests using the NordBord involving teams from the English Premier League, English Championship and UEFA Champions League; it was found that the players used in this study have similar hamstring strength scores as those playing in the English Premier League (425 N) and slightly better strength scores than English Championship (418 N) and UEFA Champions League players (400 N), respectively (Vald Performance, 2020). These values would suggest that hamstring strength is not necessarily influenced by playing level, with arguably the highest stage of Club football (UEFA Champions League) displaying the lowest scores out of the three. Additionally, the physical demands are found to be very similar between the UEFA Champions League and English Premier League competitions. In an analysis completed by "SkillCorner", the UEFA Champions League was shown to have similarities in the amount of average number of high-intensity and sprints activities and average sprint distance compared to the English Premier League. Differences were only found in the average peak sprint velocity, with the English Premier League displaying higher values (SkillCorner, 2020). In our study, a similar trend was found when the hamstring strength scores were observed based on playing position. It was found that attackers have the highest strength scores, followed by defenders and midfielders, respectively. This trend corresponds with the respective maximum velocities of these positions, with strikers being the quickest, followed by defenders and then midfielders. These findings suggest that faster players tend to have stronger eccentric hamstring strength and would further highlight why, unexpectedly, very few trends are found showing attacking players to be more susceptible to hamstring injury, unless previously injured, as discussed above (Hagglund et al., 2013b). The greater hamstring scores associated with higher maximum velocities also correspond with the analyses conducted by SkillCorner and Vald Performance showing the English Premier League to have the highest average peak velocity and hamstring strength scores, respectively, even compared to the highest stage of Club competition - the UEFA Champions League. These trends suggest, therefore, that it is important for practitioners to ensure that the players with higher maximum velocities and sprint demands also correspond with having the highest eccentric hamstring strength values in relation to the squad average. Additionally, for those individuals it may be required to increase their minimum threshold well above the recommended level of 337 N to reduce hamstring injury risk.

4.7 Limitations and Practical Implications

The main limitation of the study of reliability and validity of the NordBord was the small sample size (n = 6-7) and heterogeneity of the participants. For future studies, recruiting a larger sample size of participants with experience of performing the NHE would be beneficial. If no participants with previous experience of performing the NHE can be obtained then a thorough familiarisation period with a minimum of 2-3 sessions would be required. Additionally, when completing isometric testing it is recommended that the participant be braced in the required position to limit the influence of the gluteal muscles on the contraction.

As the main study was observational, one of the limitations was that there were many occasions that data could not be collected for various reasons, for example: in weeks consisting of multiple matches, completing the NHE was not possible as the focus during that week would be on recovery and 'muscle freshness', and during international breaks, where players would either be with their respective nations or given time off. These are, however, common issues amongst most sports teams and therefore would be difficult to overcome (Buchheit, 2017).

The overall objective of this study was to determine whether sprinting has an influence on eccentric hamstring strength in an attempt to reduce injury risk. Although it was established that eccentric hamstring strength is one of the risk factors in hamstring injury, this study did not directly measure injury risk. As there can be many influencing factors, this makes it difficult to conclude whether managing sprint loads will in fact reduce injuries; however, we know that to reduce the risk of injuries we must mitigate the factors involved. As we were able to establish that performing 7-8 weekly efforts at $\text{max}_{>90\%}$, significantly reduces eccentric hamstring strength, one can imply that there is also an increased risk of hamstring injury when reaching this amount of weekly efforts, based on hamstring strength being a risk factor of injury. However, to better understand the injury risk associated with sprinting it would also be beneficial to study its effects on other risk factors of hamstring injury, such as those mentioned in section 1.3, allowing practitioners to identify all the causes of injury and consider preventative strategies accordingly.

It has been established by previous research that practitioners should dose players with maximal effort sprints throughout the training week and the findings of this study suggest that they can be confident that obtaining >90% of each player's maximal velocity is beneficial in conditioning the hamstring muscles and maintaining their strength. However, careful monitoring is required to ensure that players do not exceed 7-8 efforts per week to maintain their eccentric hamstring strength levels. There is a possibility that these values are influenced by the ACWR; therefore, it would be beneficial for future studies to investigate a link between the ACWR, weekly efforts at $\text{max}_{>90\%}$ and hamstring strength to identify whether different thresholds are found based on different chronic loads. To adopt these findings in other sports, practitioners may need to tailor their prescribed sprint loads based on the physical demands of their sport and the chronic loads of their athletes, where sports with less sprint demands may have a lower threshold of efforts at $\text{max}_{>90\%}$, before eccentric hamstring strength decreases.

5. Conclusion

Performing the Nordic Hamstring Exercise on a NordBord is a reliable and valid method of measuring peak hamstring force. Its ease of use and portability compared to the isokinetic dynamometer makes it a helpful tool in determining hamstring strength, imbalances between limbs and as a method of providing a training stimulus to address these issues. Given the reliability of the NordBord, it was crucial for participants to be well practiced and familiar with the Nordic Hamstring Exercise before commencing research.

From this study, it can be concluded that eccentric hamstring strength levels significantly decrease when 7-8 weekly sprint efforts at $\text{max}_{>90\%}$ are completed but total weekly sprint distance or the weekly number of sprint efforts completed at $\text{max}_{>95\%}$ have no significant influence on eccentric hamstring strength. The reason that no relationship was found between eccentric hamstring strength and sprints at $\text{max}_{>95\%}$ was largely due to the limited number of efforts recorded, making it difficult to conclude whether there is any additional benefit to exposing players to efforts greater than 95% of a player’s maximum velocity. Based on the physical demands of football during training and matches and uncertain GPS accuracy at maximal velocities, it is suggested that practitioners use $\text{max}_{>90\%}$ when monitoring training and match load, ensuring that players do not exceed 7-8 efforts per week to maintain good eccentric hamstring strength levels, thereby reducing the risk of potential injury.

6. References

Aagaard, P., Simonsen, E.B., Magnusson, S.P., Larsson, B. and Dyhre-Poulsen, P. (1998) A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *The American Journal of Sports Medicine,* 26 (2), pp. 231-237.

Abbott, W., Brickley, G. and Smeeton, N.J. (2018) Physical demands of playing position within English Premier League academy soccer.

Anderson, L., Orme, P., Di Michele, R., Close, G.L., Morgans, R., Drust, B. and Morton, J.P. (2016) Quantification of training load during one-, two-and three-game week schedules in professional soccer players from the English Premier League: implications for carbohydrate periodisation. *Journal of Sports Sciences,* 34 (13), pp. 1250-1259.

Andrzejewski, M., Chmura, J., Pluta, B. and Konarski, J.M. (2015) Sprinting activities and distance covered by top level Europa league soccer players. *International Journal of Sports Science & Coaching,* 10 (1), pp. 39-50.

Arnason, A., Andersen, T., Holme, I., Engebretsen, L. and Bahr, R. (2008) Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian Journal of Medicine & Science in Sports,* 18 (1), pp. 40-48.

Arnason, A., Sigurdsson, S.B., Gudmundsson, A., Holme, I., Engebretsen, L. and Bahr, R. (2004) Risk factors for injuries in football. *The American Journal of Sports Medicine,* 32 (1_suppl), pp. 5-16.

Bangsbo, J. (2014) Physiological demands of football. *Sports Science Exchange,* 27 (125), pp. 1-6.

Bangsbo, J., Mohr, M. and Krustrup, P. (2006) Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Sciences,* 24 (07), pp. 665-674.

Bangsbo, J., Norregaard, L. and Thorso, F. (1991) Activity profile of competition soccer. *Canadian Journal of Sport Sciences = Journal Canadien Des Sciences Du Sport,* 16 (2), pp. 110-116.

Barnes, C., Archer, D., Hogg, B., Bush, M. and Bradley, P. (2014) The evolution of physical and technical performance parameters in the English Premier League. *International Journal of Sports Medicine,* 35 (13), pp. 1095-1100.

Bourne, M.N., Opar, D.A., Williams, M.D. and Shield, A.J. (2015) Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. *The American Journal of Sports Medicine,* 43 (11), pp. 2663-2670.

Bowen, L., Gross, A.S., Gimpel, M., Bruce-Low, S. and Li, F.X. (2020) Spikes in acute:chronic workload ratio (ACWR) associated with a 5-7 times greater injury rate in English Premier League football players: a comprehensive 3-year study. *British Journal of Sports Medicine,* 54 (12), pp. 731-738.

Bowen, L., Gross, A.S., Gimpel, M. and Li, F.X. (2017) Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *British Journal of Sports Medicine,* 51 (5), pp. 452-459.

Bradley, P.S., Carling, C., Diaz, A.G., Hood, P., Barnes, C., Ade, J., Boddy, M., Krustrup, P. and Mohr, M. (2013) Match performance and physical capacity of players in the top three competitive standards of English professional soccer. *Human Movement Science,* 32 (4), pp. 808-821.

Buchheit, M., Cholley, Y., Nagel, M. and 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), pp. 721-726.

Buchheit, M. (2017) Applying the acute:chronic workload ratio in elite football: worth the effort? *British Journal of Sports Medicine,* 51 (18), pp. 1325-1327.

Bush, M., Barnes, C., Archer, D.T., Hogg, B. and Bradley, P.S. (2015) Evolution of match performance parameters for various playing positions in the English Premier League. *Human Movement Science,* 39, pp. 1-11.

Carling, C., Le Gall, F. and Orhant, E. (2011) A four-season prospective study of muscle strain reoccurrences in a professional football club. *Research in Sports Medicine,* 19 (2), pp. 92-102.

Castillo, D., Raya-González, J., Yanci, J. and Clemente, F.M. (2021) Influence of pitch size on short-term high intensity actions and body impacts in soccer sided games. *Journal of Human Kinetics,* 78, pp. 187.

Colby, M.J., Dawson, B., Peeling, P., Heasman, J., Rogalski, B., Drew, M.K. and Stares, J. (2018) Improvement of prediction of noncontact injury in elite Australian Footballers with repeated exposure to established high-risk workload scenarios. *International Journal of Sports Physiology and Performance,* 13 (9), pp. 1130-1135.

Cometti, G., Maffiuletti, N., Pousson, M., Chatard, J. and Maffulli, N. (2001) Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International Journal of Sports Medicine,* 22 (01), pp. 45-51.

Cormack, S.J., Newton, R.U., McGuigan, M.R. and Doyle, T.L. (2008) Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance,* 3 (2), pp. 131-144.

Coutts, A.J., Quinn, J., Hocking, J., Castagna, C. and Rampinini, E. (2010) Match running performance in elite Australian Rules Football. *Journal of Science and Medicine in Sport,* 13 (5), pp. 543-548.

Cummins, C., Orr, R., O'Connor, H. and West, C. (2013) Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine,* 43 (10), pp. 1025-1042.

Cummins, C., Welch, M., Inkster, B., Cupples, B., Weaving, D., Jones, B., King, D. and Murphy, A. (2019) Modelling the relationships between volume, intensity and injury-risk in professional rugby league players. *Journal of Science and Medicine in Sport,* 22 (6), pp. 653-660.

Cumps, E., Verhagen, E., Annemans, L. and Meeusen, R. (2008) Injury rate and socioeconomic costs resulting from sports injuries in Flanders: data derived from sports insurance statistics 2003. *British Journal of Sports Medicine,* 42 (9), pp. 767-772.

de Visser, H.M., Reijman, M., Heijboer, M.P. and Bos, P.K. (2012) Risk factors of recurrent hamstring injuries: a systematic review. *British Journal of Sports Medicine,* 46 (2), pp. 124-130.

Dellal, A., Chamari, K., Wong, d.P., Ahmaidi, S., Keller, D., Barros, R., Bisciotti, G.N. and Carling, C. (2011) Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. *European Journal of Sport Science,* 11 (1), pp. 51-59.

Dellal, A., Wong, d.P., Moalla, W. and Chamari, K. (2010) Physical and technical activity of soccer players in the French First League-with special reference to their playing position. *International SportMed Journal,* 11 (2), pp. 278-290.

Department of Health (2015) *NHS Reference Costs 2015-16.* Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/577083/Reference_Costs_2015-16.pdf [Accessed: 28/11/2019].

Devismes, M., Aeles, J., Philips, J. and Vanwanseele, B. (2021) Sprint force-velocity profiles in soccer players: impact of sex and playing level. *Sports Biomechanics*, 20 (8), pp. 947-957.

Di Mascio, M. and Bradley, P.S. (2013) Evaluation of the most intense high-intensity running period in English FA premier league soccer matches. *The Journal of Strength & Conditioning Research*, 27 (4), pp. 909-915.

Di Salvo, V., Baron, R., Tschan, H., Montero, F.C., Bachl, N. and Pigozzi, F. (2007) Performance characteristics according to playing position in elite soccer. *International Journal of Sports Medicine*, 28 (03), pp. 222-227.

Di Salvo, V., Baron, R., González-Haro, C., Gormasz, C., Pigozzi, F. and Bachl, N. (2010) Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. *Journal of Sports Sciences*, 28 (14), pp. 1489-1494.

Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P. and Drust, B. (2009) Analysis of high intensity activity in Premier League soccer. *International Journal of Sports Medicine*, 30 (03), pp. 205-212.

Domene, A.M. (2013) Evaluation of movement and physiological demands of full-back and center-back soccer players using global positioning systems. *Journal of Human Sport and Exercise,* 8 (4), pp. 1015-1028.

Duhig, S., Shield, A.J., Opar, D., Gabbett, T.J., Ferguson, C. and Williams, M. (2016) Effect of high-speed running on hamstring strain injury risk. *British Journal of Sports Medicine*, 50 (24), pp. 1536-1540.

Ekstrand, J., Hagglund, M. and Walden, M. (2011) Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine,* 45 (7), pp. 553-558.

Ekstrand, J., Krutsch, W., Spreco, A., van Zoest, W., Roberts, C., Meyer, T. and Bengtsson, H. (2020) Time before return to play for the most common injuries in professional football: a 16-year follow-up of the UEFA Elite Club Injury Study. *British Journal of Sports Medicine*, 54 (7), pp. 421-426.

Ekstrand, J., Walden, M. and Hagglund, 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), pp. 731-737.

Engebretsen, A.H., Myklebust, G., Holme, I., Engebretsen, L. and Bahr, R. (2010) Intrinsic risk factors for hamstring injuries among male soccer players: a prospective cohort study. *The American Journal of Sports Medicine,* 38 (6), pp. 1147-1153.

Faude, O., Koch, T. and Meyer, T. (2012) Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences,* 30 (7), pp. 625-631.

Feiring, D.C., Ellenbecker, T.S. and Derscheid, G.L. (1990) Test-retest reliability of the Biodex isokinetic dynamometer. *Journal of Orthopaedic & Sports Physical Therapy,* 11 (7), pp. 298-300.

Fleay, B., Joyce, C., Banyard, H. and Woods, C.T. (2018) Manipulating field dimensions during small-sided games impacts the technical and physical profiles of Australian footballers. *The Journal of Strength & Conditioning Research,* 32 (7), pp. 2039-2044.

Forbes Magazine (2019) *The World's Highest Paid Athletes*. Available: https://www.forbes.com/athletes/list/#tab:overall [Accessed: 01/12/2019].

Gabbett, T.J., Jenkins, D.G. and Abernethy, B. (2012) Physical demands of professional rugby league training and competition using microtechnology. *Journal of Science and Medicine in Sport,* 15 (1), pp. 80-86.

Gabbett, T.J., Nassis, G.P., Oetter, E., Pretorius, J., Johnston, N., Medina, D., Rodas, G., Myslinski, T., Howells, D., Beard, A. and Ryan, A. (2017) The athlete monitoring cycle: a practical guide to interpreting and applying training monitoring data. *British Journal of Sports Medicine,* 51 (20), pp. 1451-1452.

Garrett Jr, W.E. (1996) Muscle strain injuries. *The American Journal of Sports Medicine,* 24 (6_suppl), pp. S2-S8.

Gissis, I., Papadopoulos, C., Kalapotharakos, V.I., Sotiropoulos, A., Komsis, G. and Manolopoulos, E. (2006) Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Research in Sports Medicine,* 14 (3), pp. 205-214.

Hägglund, M., Waldén, M. and Ekstrand, J. (2013) Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study. *The American Journal of Sports Medicine,* 41 (2), pp. 327-335.

Hagglund, M., Walden, M., Bahr, R. and Ekstrand, J. (2005) Methods for epidemiological study of injuries to professional football players: developing the UEFA model. *British Journal of Sports Medicine,* 39 (6), pp. 340-346.

Hagglund, M., Walden, M. and 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), pp. 767-772.

Hagglund, M., Walden, M., Magnusson, H., Kristenson, K., Bengtsson, H. and Ekstrand, J. (2013) Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, 47 (12), pp. 738-742.

Haugen, T.A., Breitschädel, F. and Seiler, S. (2020) Sprint mechanical properties in soccer players according to playing standard, position, age and sex. *Journal of Sports Sciences,* 38 (9), pp. 1070-1076.

Higashihara, A., Nagano, Y., Ono, T. and Fukubayashi, T. (2015) Differences in activation properties of the hamstring muscles during overground sprinting. *Gait & Posture,* 42 (3), pp. 360-364.

Hootman, J.M., Macera, C.A., Ainsworth, B.E., Martin, M., Addy, C.L. and Blair, S.N. (2001) Association among physical activity level, cardiorespiratory fitness, and risk of musculoskeletal injury. *American Journal of Epidemiology,* 154 (3), pp. 251-258.

Hopkins, W. (2002) *A Scale of Magnitude for Effect Statistics. Internet Society for Sport Science*.

Hopkins, W.G. (2000) Measures of reliability in sports medicine and science. *Sports Medicine,* 30 (1), pp. 1-15.

Hulin, B.T., Gabbett, T.J., Lawson, D.W., Caputi, P. and Sampson, J.A. (2016) The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British Journal of Sports Medicine,* 50 (4), pp. 231-236.

Kalkhoven, J.T., Watsford, M.L., McLean, B.D. and Sides, D.L. (2020) The evidence indicates that the hamstrings do not behave isometrically during the swing phase of the sprint cycle: a narrative review.

LaStayo, P.C., Woolf, J.M., Lewek, M.D., Snyder-Mackler, L., Reich, T. and Lindstedt, S.L. (2003) Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *Journal of Orthopaedic & Sports Physical Therapy,* 33 (10), pp. 557-571.

Le Gall, F., Carling, C., Williams, M. and Reilly, T. (2010) Anthropometric and fitness characteristics of international, professional and amateur male graduate soccer players from an elite youth academy. *Journal of Science and Medicine in Sport,* 13 (1), pp. 90-95.

Lee, J.W., Mok, K., Chan, H.C., Yung, P.S. and Chan, K. (2018) Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players. *Journal of Science and Medicine in Sport,* 21 (8), pp. 789-793.

Lepschy, H., Wäsche, H. and Woll, A. (2018) How to be successful in football: a systematic review. *The Open Sports Sciences Journal,* 11 (1).

Little, T. (2009) Optimizing the use of soccer drills for physiological development. *Strength & Conditioning Journal,* 31 (3), pp. 67-74.

Liu, H., Garrett, W.E., Moorman, C.T. and 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), pp. 92-101.

Lodge, C., Tobin, D., O'Rourke, B. and Thorborg, K. (2020) Reliability and Validity of a New Eccentric Hamstring Strength Measurement Device. *Archives of Rehabilitation Research and Clinical Translation,* 2 (1), pp. 100034.

Lunnen, J.D., Yack, J. and LeVeau, B.F. (1981) Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy,* 61 (2), pp. 190-195.

Malone, J.J., Barrett, S., Barnes, C., Twist, C. and Drust, B. (2020) To infinity and beyond: the use of GPS devices within the football codes. *Science and Medicine in Football,* 4 (1), pp. 82-84.

Malone, J.J., Lovell, R., Varley, M.C. and Coutts, A.J. (2017) Unpacking the black box: applications and considerations for using GPS devices in sport. *International Journal of Sports Physiology and Performance,* 12 (s2), pp. S2-18-S2-26.

Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K. and Gabbett, T.J. (2018) High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport,* 21 (3), pp. 257-262.

Malone, S., Roe, M., Doran, D.A., Gabbett, T.J. and Collins, K. (2017) High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *Journal of Science and Medicine in Sport*, 20 (3), pp. 250-254.

Malone, S., Solan, B., Collins, K.D. and Doran, D.A. (2016) Positional match running performance in elite Gaelic football. *Journal of Strength and Conditioning Research,* 30 (8), pp. 2292-2298.

McAllister, M.J., Hammond, K.G., Schilling, B.K., Ferreria, L.C., Reed, J.P. and Weiss, L.W. (2014) Muscle activation during various hamstring exercises. *The Journal of Strength & Conditioning Research,* 28 (6), pp. 1573-1580.

Minano-Espin, J., Casais, L., Lago-Penas, C. and Gomez-Ruano, M.A. (2017) High Speed Running and Sprinting Profiles of Elite Soccer Players. *Journal of Human Kinetics,* 58, pp. 169-176.

Mjølsnes, R., Arnason, A., Østhagen, T., Raastad, T. and Bahr, R. (2004) A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine & Science in Sports,* 14 (5), pp. 311-317.

Mohr, M., Krustrup, P. and Bangsbo, J. (2003) Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences,* 21 (7), pp. 519-528.

Morin, J., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M. and Mendiguchia, J. (2015) Sprint acceleration mechanics: the major role of hamstrings in horizontal force production. *Frontiers in Physiology,* 6, pp. 404.

Murray, C.J., Richards, M.A., Newton, J.N., Fenton, K.A., Anderson, H.R., Atkinson, C., Bennett, D., Bernabé, E., Blencowe, H. and Bourne, R. (2013) UK health performance:

findings of the Global Burden of Disease Study 2010. *The Lancet,* 381 (9871), pp. 997-1020.

Murray, N.B., Gabbett, T.J., Townshend, A.D. and Blanch, P. (2017) Calculating acute:chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages. *British Journal of Sports Medicine,* 51 (9), pp. 749-754.

National Health Interview Survey (NHIS) (2012) *National Health Interview Survey* Available: www.cdc.gov/nchs/nhis/nhis_2012_data_release.htm [Accessed 25/11/2019].

Oja, P., Titze, S., Kokko, S., Kujala, U.M., Heinonen, A., Kelly, P., Koski, P. and Foster, C. (2015) Health benefits of different sport disciplines for adults: systematic review of observational and intervention studies with meta-analysis. *British Journal of Sports Medicine,* 49 (7), pp. 434-440.

Okuwaki T. (2007) The causes and predicted remedies of pulled muscles. *Sportsmedicine,* 19 (2), pp. 6-14 (In Japanese).

Ono, T., Higashihara, A., Shinohara, J., Hirose, N. and Fukubayashi, T. (2015) Estimation of tensile force in the hamstring muscles during overground sprinting. *International Journal of Sports Medicine,* 36 (02), pp. 163-168.

Opar, D.A., Piatkowski, T., Williams, M.D. and 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), pp. 636-640.

Opar, D., Williams, M., Timmins, R., Hickey, J., Duhig, S. and Shield, A. (2015) Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise,* 47 (4), pp. 857-865.

Otten, R., Whiteley, R. and Mitchell, T. (2013) Effect of subject restraint and resistance pad placement on isokinetic knee flexor and extensor strength: implications for testing and rehabilitation. *Sports Health,* 5 (2), pp. 137-142.

Parsons, S. and Symmons, D.P. (2014) The burden of musculoskeletal conditions. *Medicine,* 42 (4), pp. 190-192.

Póvoas, S.C., Seabra, A.F., Ascensão, A.A., Magalhães, J., Soares, J.M. and Rebelo, A.N. (2012) Physical and physiological demands of elite team handball. *The Journal of Strength & Conditioning Research,* 26 (12), pp. 3365-3375.

Presland, J.D., Timmins, R.G., Bourne, M.N., Williams, M.D. and 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), pp. 1775-1783.

Read, P.J., Turner, A.N., Clarke, R., Applebee, S. and Hughes, J. (2019) Knee angle affects posterior chain muscle activation during an isometric test used in soccer players. *Sports,* 7 (1), pp. 13.

Ritti-Dias, R.M., Avelar, A., Salvador, E.P. and Cyrino, E.S. (2011) Influence of previous experience on resistance training on reliability of one-repetition maximum test. *The Journal of Strength & Conditioning Research,* 25 (5), pp. 1418-1422.

Ross, S. (2020) Reliability and comparison of force characteristics of the Nordic hamstring exercise. *ISBS Proceedings Archive,* 38 (1), pp. 784.

Šarabon, N., Marušič, J., Marković, G. and Kozinc, Ž. (2019) Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. *PloS One,* 14 (10), pp. e0223437.

Schache, A.G., Dorn, T.W., Blanch, P.D., Brown, N.A. and Pandy, M.G. (2012) Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise,* 44 (4), pp. 647-658.

Schimpchen, J., Skorski, S., Nopp, S. and Meyer, T. (2016) Are “classical” tests of repeated-sprint ability in football externally valid? A new approach to determine in-game sprinting behaviour in elite football players. *Journal of Sports Sciences,* 34 (6), pp. 519-526.

Schuermans, J., Van Tiggelen, D., Danneels, L. and Witvrouw, E. (2016) Susceptibility to hamstring injuries in soccer: a prospective study using muscle functional magnetic resonance imaging. *The American Journal of Sports Medicine,* 44 (5), pp. 1276-1285.

Scott, M.T., Scott, T.J. and Kelly, V.G. (2016) The Validity and Reliability of Global Positioning Systems in Team Sport: A Brief Review. *Journal of Strength and Conditioning Research,* 30 (5), pp. 1470-1490.

Shvili, J. (2020) *The Most Popular Sports in The World* Available: https://www.worldatlas.com/articles/what-are-the-most-popular-sports-in-the-world.html [Accessed: 27/09/2021]

Silva, L.M., Neiva, H.P., Marques, M.C., Izquierdo, M. and Marinho, D.A. (2018) Effects of warm-up, post-warm-up, and re-warm-up strategies on explosive efforts in team sports: A systematic review. *Sports Medicine*, 48 (10), pp. 2285-2299.

SkillCorner (2020) *Competing at the Pinnacle: Physical Demands of the UEFA Champions League* Available: https://medium.com/skillcorner/competing-at-the-pinnacle-physical-demands-of-the-uefa-champions-league-278399632d80 [Accessed: 15/11/2021]

Slimani, M. and Nikolaidis, P.T. (2017) Anthropometric and physiological characteristics of male Soccer players according to their competitive level, playing position and age group: a systematic review. *J Sports Med Phys Fitness*, 59 (1), pp. 141-163.

Stambulova, N., Stephan, Y. and Jäphag, U. (2007) Athletic retirement: A cross-national comparison of elite French and Swedish athletes. *Psychology of Sport and Exercise*, 8 (1), pp. 101-118.

Stauber, W.T. (1989) Eccentric action of muscles: physiology, injury, and adaptation. *Exercise and Sport Sciences Reviews*, 17, pp. 157-185.

Taanila, H., Suni, J.H., Kannus, P., Pihlajamäki, H., Ruohola, J., Viskari, J. and Parkkari, J. (2015) Risk factors of acute and overuse musculoskeletal injuries among young conscripts: a population-based cohort study. *BMC Musculoskeletal Disorders*, 16 (1), pp. 1-19.

Timmins, R.G., Bourne, M.N., Shield, A.J., Williams, M.D., Lorenzen, C. and 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), pp. 1524-1535.

Tobin, D. (2017) *An Investigation into the Acute Effects of Utilising a Live Strength Feedback System to Ensure Equal Bilateral Force Distribution when Performing the Nordic Hamstring Exercise, a Randomised Control Trial*.

Vald Performance (2020) *European Football Report Season 2019-20: Nordic Strength* Available: https://valdperformance.com/nordic-strength/ [Accessed: 21/10/2021] van der Horst, N., Backx, F., Goedhart, E.A., Huisstede, B.M. and HIPS-Delphi Group. (2017) Return to play after hamstring injuries in football (soccer): a worldwide Delphi procedure regarding definition, medical criteria and decision-making. *British Journal of Sports Medicine,* 51 (22), pp. 1583-1591.

Varley, M.C., Jaspers, A., Helsen, W.F. and Malone, J.J. (2017) Methodological considerations when quantifying high-intensity efforts in team sport using global positioning system technology. *International Journal of Sports Physiology and Performance,* 12 (8), pp. 1059-1068.

Vos, T., Abajobir, A.A., Abate, K.H., Abbafati, C., Abbas, K.M., Abd-Allah, F., Abdulkader, R.S., Abdulle, A.M., Abebo, T.A. and Abera, S.F. (2017) Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet,* 390 (10100), pp. 1211-1259.

Vos, T., Barber, R.M., Bell, B., Bertozzi-Villa, A., Biryukov, S., Bolliger, I., Charlson, F., Davis, A., Degenhardt, L. and Dicker, D. (2015) Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet,* 386 (9995), pp. 743-800.

Whiteley, R., Jacobsen, P., Prior, S., Skazalski, C., Otten, R. and Johnson, A. (2012) Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. *Journal of Science and Medicine in Sport,* 15 (5), pp. 444-450.

Wiesinger, H., Gressenbauer, C., Kösters, A., Scharinger, M. and Müller, E. (2020) Device and method matter: A critical evaluation of eccentric hamstring muscle strength assessments. *Scandinavian Journal of Medicine & Science in Sports,* 30 (2), pp. 217-226.

Woods, C., Hawkins, R.D., Maltby, S., Hulse, M., Thomas, A., Hodson, A. and Football Association Medical Research Programme. (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), pp. 36-41.

World Health Organization (2019) *Musculoskeletal Conditions*
Available: https://www.who.int/news-room/fact-sheets/detail/musculoskeletal-conditions [Accessed: 25/11/2019].

Worrell, T.W., Perrin, D.H. and Denegar, C.R. (1989) The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *Journal of Orthopaedic & Sports Physical Therapy,* 11 (3), pp. 104-107.

Yu, B., Queen, R.M., Abbey, A.N., Liu, Y., Moorman, C.T. and Garrett, W.E. (2008) Hamstring muscle kinematics and activation during overground sprinting. *Journal of Biomechanics,* 41 (15), pp. 3121-3126.

7. Appendices

Appendix A. Injury pattern with severity of injuries (adapted from Ekstrand et al., 2011)

	Total	**1-3 Days**	**4-7 Days**	**8-28 Days**	**>28 Days**
Injury Location					
Head & neck	77 (2)	19	23	29	6
Neck/cervical spine	23	11	8	3	1
Shoulder/clavicula	80 (2)	12	16	30	22
Upper arm	3	1	2	0	0
Elbow	24	3	10	8	3
Forearm	5	1	0	2	2
Wrist	8	1	1	4	2
Hand/finger/thumb	38	8	6	16	8
Sternum/ribs/upper back	47 (1)	9	16	19	3
Abdomen	31	3	7	17	4
Lower back/pelvis	237 (5)	74	78	66	19
Hip/groin	616 (14)	119	169	256	72
Thigh	1064 (23)	184	272	469	139
Knee	818 (18)	183	155	268	212
Lower leg/Achilles tendon	511 (11)	116	132	178	85
Ankle	625 (14)	150	185	220	70
Foot/toe	268 (6)	75	81	63	49
Unknown	8	2	3	3	0
Injury Type					
Fracture	160 (4)	7	9	59	85
Other bone injury	26	5	1	6	14
Dislocation/subluxation	50 (1)	5	4	24	17
Sprain/ligament injury	828 (18)	123	197	334	174
Meniscus/cartilage	124 (3)	3	7	41	73
Muscle injury/strain	1581 (35)	212	397	765	207
Tendon injury	327 (7)	95	71	101	60
Haematoma/contusion	744 (17)	306	282	141	15
Abrasion	7	3	3	1	0
Laceration	31	10	11	10	0
Concussion	34	5	14	14	1
Nerve injury	29	7	3	14	5
Synovitis/effusion	158 (4)	55	36	55	12
Overuse complaints	285 (6)	110	99	59	17
Other types	91 (2)	23	27	24	17
Total Injuries	**4483**	**971**	**1164**	**1651**	**697**

Values within brackets show percentage of total (values below 1% not shown).

Appendix B. Review of positional differences for total, high-speed running and sprint distances covered during match-play in various leagues (mean ± SD)

Author	**Playing Level of Participants**	**Total Distance (m)**	**High-Speed Running Distance (m)**	**Sprinting Distance (m)**
Di Salvo et al. (2007)	La Liga and UEFA Champions League	Central Defence: 10,627 ± 893 External Defence: 11,410 ± 708 Central Midfield: 12,027 ± 625 External Midfield: 11,990 ± 776 Forward: 11,254 ± 894	Central Defence: 397 ± 114 External Defence: 652 ± 179 Central Midfield: 627 ± 184 External Midfield: 738 ± 174 Forward 621: ± 161	Central Defence: 215 ± 100 External Defence: 402 ± 165 Central Midfield: 248 ± 116 External Midfield: 446 ± 161 Forward: 404 ± 140
Dellal et al. (2011)	La Liga	Central Defence: 10,496 ± 772 Full Back: 10,650 ± 786 Central Defensive Midfield: 11,247 ± 914 Central Attacking Midfield: 11,005 ± 1,164 Wide Midfield: 11,241 ± 762 Forward: 10,718 ± 901	Central Defence: 226 ± 54 Full Back: 285 ± 55 Central Defensive Midfield: 280 ± 66 Central Attacking Midfield: 278 ± 61 Wide Midfield: 311 ± 67 Forward: 289 ± 56	Central Defence: 194 ± 65 Full Back: 249 ± 77 Central Defensive Midfield: 203 ± 76 Central Attacking Midfield: 222 ± 67 Wide Midfield: 251 ± 72 Forward: 260 ± 73

Appendix B. (Continued)

Dellal et al. (2011)	English Premier League	Central Defence: 10,617 ± 858 Full Back: 10,775 ± 656 Central Defensive Midfield: 11,556 ± 811 Central Attacking Midfield: 11,780 ± 706 Wide Midfield: 11,041 ± 757 Forward: 10,802 ± 992	Central Defence: 241 ± 64 Full Back: 270 ± 55 Central Defensive Midfield: 319 ± 68 Central Attacking Midfield: 334 ± 61 Wide Midfield: 298 ± 62 Forward: 300 ± 64	Central Defence: 209 ± 69 Full Back: 263 ± 70 Central Defensive Midfield: 246 ± 78 Central Attacking Midfield: 267 ± 64 Wide Midfield: 259 ± 85 Forward: 278 ± 78
Andrzejewski et al. (2015)	UEFA Europa League	Central Defence: 10,336 ± 471 External Defence: 11,063 ± 791 Central Midfield: 11,760 ± 797 External Midfield: 11,746 ± 690 Forward: 10,940 ± 648	Not reported	Central Defence: 186 ± 82 External Defence: 265 ± 121 Central Midfield: 167 ± 87 External Midfield: 314 ± 123 Forward: 346 ± 130
Abbott et al. (2018)	English Premier League U23's	Central Defence: 9,830 ± 428 Wide Defence: 10,747 ± 420 Central Midfield: 11,570 ± 469 Wide Attack: 10,918 ± 353 Striker: 10,320 ± 420	Refer to Figure 1 in Abbott el., (2018)	Refer to Figure 1 in Abbott el., (2018)