A multifactorial and individualized approach to reduce hamstring muscle injuries in professional football players.

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THÈSE DE DOCTORAT

Approche multifactorielle et individualisée pour prévenir les blessures aux ischio-jambiers chez les joueurs de football professionnels.

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A multifactorial and individualized approach to reduce hamstring muscle injuries in professional football players.

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ABSTRACT (ENGLISH)

Despite efforts to intervene, hamstring muscle injuries (HMI) continue to be one of the largest epidemiological burdens in professional football. The injury mechanism takes place dominantly during sprinting, but also other scenarios have been observed, such as overstretching actions, jumps, and change of directions. The main biomechanical roles of the hamstring muscles are functioning as an accelerator of center-of-mass (i.e., contributing to horizontal force production), and stabilizing the pelvis and knee joint. Multiple extrinsic and intrinsic risk factors have been identified, portraying the multifactorial nature of the HMI. Furthermore, these risk factors can vary substantially between players, portraying the importance of individualized approaches. However, there is a lack of multifactorial and individualized approaches assessed for validity in literature. Thus, the overarching aim of this doctoral thesis was to explore if a specific multifactorial and individualized approach can improve upon the ongoing HMI risk reduction protocols, and thus, further reduce the HMI risk in professional football players. This was done following the Team-sport Injury Prevention model (TIP model), where the target is to evaluate the current injury burden, identify possible solutions, and intervene. The thesis comprised of three themes within professional football, I) evaluating and identifying HMI risk (completed via assessing the current epidemiological HMI situation and the association between HMI injuries and a novel hamstring screening protocol), II) improving horizontal force capacity (completed via testing if maximal theoretical horizontal force ($F0$) can be improved via heavy resisted sprint training), and III) developing and conducting a multifactorial and individualized training for HMI risk reduction (completed via introducing and conducting a training intervention). The conclusions from theme I were that the HMI burden continues to be high (14.1 days absent per 1000 hours of football exposure), no tests from the screening protocol were associated with an increased HMI risk when including all injuries from the season ($n = 17$, $p > 0.05$), and that lower $F0$ was significantly associated with increased HMI risk when including injuries between test rounds one and two (~90 days, $n = 14$, hazard ratio: 4.02 (CI95% 1.08 to 15.0), $p = 0.04$). For theme II, the players initial pre-season level of $F0$ was significantly associated with adaptation potential after 11 weeks of heavy resisted sprint training during the pre-season ($r = -0.59$, $p < 0.05$). The heavy resisted sprint load leading to a ~50% velocity loss induced the largest improvements in sprint mechanical output and sprint performance variables. For theme III, no intervention results could be presented within this document due to the Covid-19 pandemic leading to the intervention being postponed. However, a protocol paper was published, describing in detail the intervention approach that will be used outside the scope of the thesis. In future studies, larger sample size studies are needed to support the development of more advanced HMI risk reduction models. Such models may allow practitioners to identify risk on an individual level instead of a group level. Furthermore, constant development of more specific, reliable, and accessible risk assessment tests should be promoted that can be frequently tested throughout the football season. Finally, based on the results of theme II, individualization of a specific training stimulus should be promoted in team settings.

Keywords: Injury prevention, soccer, multifactorial, individualization.

ABSTRACT (FRENCH)

Malgré les efforts déployés pour mieux les comprendre et les prévenir, les lésions des muscles ischio-jambiers (LIJ) continuent d'être un phénomène épidémiologique majeur et irrésolu dans le football professionnel. Le principal mécanisme de blessure a lieu pendant le sprint, mais d'autres scénarios ont également été observés, tels que des actions d'étirement excessif, des sauts et des changements de direction. Dans un de leurs rôle biomécanique les ischio-jambiers fonctionnent comme un accélérateur du centre de masse (c'est-à-dire qu'ils contribuent à la production de force horizontale sur le sol) et stabilisent le bassin et l'articulation du genou. De multiples facteurs de risque extrinsèques et intrinsèques ont été identifiés, décrivant la nature multifactorielle de la blessure. De plus, ces facteurs de risque peuvent varier considérablement entre coéquipiers, ce qui montre l'importance des approches individualisées. Cependant, la validité d'approches multifactorielles et individualisées a peu été évaluée dans la littérature. Ainsi, l'objectif global de cette thèse de doctorat était d'explorer si une approche multifactorielle et individualisée spécifique peut améliorer les protocoles de réduction des risques de LIJ, et ainsi, réduire le risque de LIJ dans le football professionnel. Cette problématique a été abordé selon le modèle de prévention des blessures dans les sports collectifs (modèle TIP), où l'objectif est d'évaluer l'état actuel des blessures, d'identifier des solutions possibles et d'intervenir. La thèse comprenait trois thèmes appliqués au football professionnel : I) Évaluation et identification des risques de blessures aux ischio-jambiers (en évaluant la situation épidémiologique actuelle de LIJ et l'association entre les blessures de type LIJ et un nouveau protocole de dépistage), II) Améliorer la capacité de production de force horizontale (en testant si la force horizontale théorique maximale (F*0*) en sprint peut être améliorée via un entraînement au sprint à haute résistance), et III) Proposer une intervention multifactorielle et individualisée pour la réduction des risques de LIJ (complété par l'introduction d'une étude interventionnelle). Les conclusions du thème I étaient que la charge représentée par les LIJ continue d'être élevée (14.1 jours d'absence pour 1000 heures d'exposition au football), aucun test du protocole de dépistage n'a été associé à un risque accru de LIJ en incluant toutes les blessures de la saison ($n = 17$, $p > 0.05$), et qu'un F*0* plus faible était significativement associé à un risque accru de LIJ lors de l'inclusion séparée de blessures apparues entre les cycles de test un et deux (~90 jours, $n = 14$, hazard ratio: 4.02, IC à 95 %: 1.08 – 15.0, $p =0.04$). Pour le thème II, le niveau initial de F*0* des joueurs avant intervention était significativement associé au potentiel d'adaptation après 11 semaines d'entraînement intensif au sprint avec résistance pendant la pré-saison ($r = -0.59$, $p < 0.05$). L'entrainement avec charge élevée de résistance en sprint (conduisant à une perte de vitesse d'environ 50 %) a induit les plus grandes améliorations de la production mécanique et de la performance lors de l'accélération en sprint. Pour le thème III, aucun résultat de l'étude interventionnelle n'a pu être présenté en raison de la pandémie de Covid-19 ayant entraîné son report. Cependant, le protocole a été publié, décrivant en détail l'approche interventionnelle utilisée actuellement, en dehors du cadre de la thèse. Des études futures de plus grande taille sont nécessaires pour soutenir le développement de modèles d'identification des risques de LIJ plus avancés. De tels modèles peuvent permettre aux praticiens de mieux identifier les risques au niveau individuel plutôt qu'au niveau d'un groupe. De plus, il convient de promouvoir le développement constant de tests d'évaluation des risques plus spécifiques, fiables et accessibles, pouvant être fréquemment répétés tout au long de la saison de football. Enfin, sur la base des résultats du thème II, l'individualisation d'un stimulus d'entraînement spécifique devrait être favorisée au sein du groupe équipe.

Mots clés: Prévention des blessures, soccer, multifactorial, individualisation.

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Publications in international peer reviewed journals (As they appear in text):

1. Lahti J, Huuhka T, Romero V, Bezodis I, Morin J, Häkkinen K (2020). Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players. PeerJ 8:e10507.
2. Lahti J, Mendiguchia J, Edouard P, Morin JB. A novel multifactorial musculoskeletal hamstring screening protocol: association with hamstring muscle injuries in professional football (soccer) – a prospective cohort study. In second revision. Biology of Sport.
3. Lahti J, Mendiguchia J, Ahtiainen J, Anula L, Kononen T, Kujala M, Matinlauri A, Peltonen V, Thibault M, Toivonen RM, Edouard P, Morin JB (2020). Multifactorial individualised programme for hamstring muscle injury risk reduction in professional football: protocol for a prospective cohort study. BMJ Open Sport & Exercise Medicine. **6:**e000758.

Other peer-reviewed publications relevant to the thesis:

1. Edouard P, Lahti J, Nagahara R, Samozino P, Navarro L, Guex K, Rossi J, Brughelli M, Mendiguchia J, Morin JB (2021). Low Horizontal Force Production Capacity during Sprinting as a Potential Risk Factor of Hamstring Injury in Football. Int J Environ Res Public Health. 18(15):7827.
2. Prince C, Morin JB, Mendiguchia J, Lahti J, Guex K, Edouard P, Samozino P (2021). Sprint Specificity of Isolated Hamstring-Strengthening Exercises in Terms of Muscle Activity and Force Production. Frontiers in Sports and Active Living. 2: 221.
3. Lahti J, Jiménez-Reyes P, Cross MR, Samozino P, Chassaing P, Simond-Cote B, Ahtiainen JP, Morin JB (2020). Individual Sprint Force-Velocity Profile Adaptations to In-Season Assisted and Resisted Velocity-Based Training in Professional Rugby. Sports. 8(5):74.
4. Hegyi A, Lahti J, Giacomo JP, Gerus P, Cronin N, Morin JB (2019). Impact of hip flexion angle on unilateral and bilateral Nordic hamstring exercise torque and high-density electromyography activity. Journal of Orthopaedic and Sports Physical Therapy. 49(8):584-592.
5. Cross MR, Lahti J, Brown SR, Chedati M, Jimenez-Reyes P, Samozino P, Eriksrud O, Morin JB (2018). Training at maximal power in resisted sprinting: Optimal load determination methodology and pilot results in team sport athletes. PLoS One. 13(4):e0195477.
6. Edouard P, Mendiguchia J, Lahti, Arnal P, Gimenez P, Jiménez-Reyes P, Brughelli M, Samozino P, and Morin JB (2018). Sprint Acceleration Mechanics in Fatigue Conditions: Compensatory Role of Gluteal Muscles in Horizontal Force Production and Potential Protection of Hamstring Muscles. Frontiers in Physiology. 9: 1706.

Other noteworthy publications (non-peer reviewed):

1. Lahti J, Mendiguchia J, Edouard P, Morin JB (2021). Inter-day test-retest intrarater reliability of a multifactorial musculoskeletal hamstring screening protocol for football players: A Pilot Study, Sport Perform Sci Reports, 1: 143. https://sportperfsci.com/inter-day-test-retest-intrarater-reliability-of-a-multifactorial-musculoskeletal-hamstring-screening-protocol-for-football-players-a-pilot-study/

2. Edouard P, Mendiguchia J, Guex K, Lahti J, Samozino P, Morin JB. Sprinting: a potential vaccine for hamstring injury? Sports performance & Science Reports. https://sportperfsci.com/sprinting-a-potential-vaccine-for-hamstring-injury/

3. Giacomo JP, Lahti J, Heygi A, Gerus P, Morin JB (2018). Sport Performance & Science Reports. A new testing and training device for hamstring muscle function. https://sportperfsci.com/a-new-testing-and-training-device-for-hamstring-muscle-function/

Oral presentations relevant to the thesis:

Lahti J, Giacomo JP, Hegyi A, Noule T, Gerus P, Morin JB (2018). Conference paper & presentation: Nordic hamstring exercise torque and sprint acceleration mechanical profile and performance in team sport athletes; are they related? World Congress of Biomechanics, Dublin Ireland. https://app.oxfordabstracts.com/stages/123/programme-builder/submission/20374?backHref=/events/123/sessions/145&view=published

Poster presentations relevant to the thesis:

Lahti J, Hegyi A, Giacomo JP, Noule T, Gerus P, Morin JB (2018). Effects of hip flexion angle on the nordic hamstring exercise high-density EMG acticity completed in submaximal and fatiguing conditions. Conference: ICST 2018.
https://tinyurl.com/33pts2ft

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1.4. ABBREVIATIONS

ACL: Anterior Cruciate Ligament

ACLR: Anterior Cruciate Ligament Reconstruction

APT: Anterior Pelvic Tilt

BFlh: Biceps Femoris Long Head

BFsh: Biceps Femoris Short Head

BM: Body-Mass

FL: Fascicle Length

F*0*: Maximal Theoretical Horizontal Force

FIFA: International Federation of Association Football

GPS: Global Positioning System

GRF: Ground reaction force

HMI: Hamstring Muscle Injury

ML: Muscle length

MTU: Muscle-Tendon Unit

MVC: Maximal Voluntary Isometric Contraction

NHE: Nordic Hamstring Exercise

PCSA: Physiological Cross Sectional Area

RCT: Randomized control trial

RTP: Return to play

SM: Semimembranosus

SSC: Stretch Shortening Cycle

ST: Semitendinosus

1.5. THESIS STRUCTURE

In Figure 1 the thesis structure is presented. The thesis is built into 8 chapters. This includes an overview, scientific background, three main themes, discussion, bibliography, and appendices. The three themes aim to chronologically target the thesis questions and aims. Each theme is divided into three parts, which provide deeper insight to the publication(s) belonging to that theme. This includes a scientific background behind the questions and aim of the theme, the chosen research methods and their logic, the publication itself, and an open discussion of the results.

In general, the thesis follows the Team-sport Injury Prevention model (TIP model) presented in section 2.5 (O'brien *et al.,* 2019). The TIP model provides a structure for approaching an epidemiological problem in team sports, which is divided into three phases; (re)evaluation, identification, and intervening. Theme I focuses on evaluation and identification, theme II focuses on piloting for the final phase of intervening, and theme III focuses on intervening.

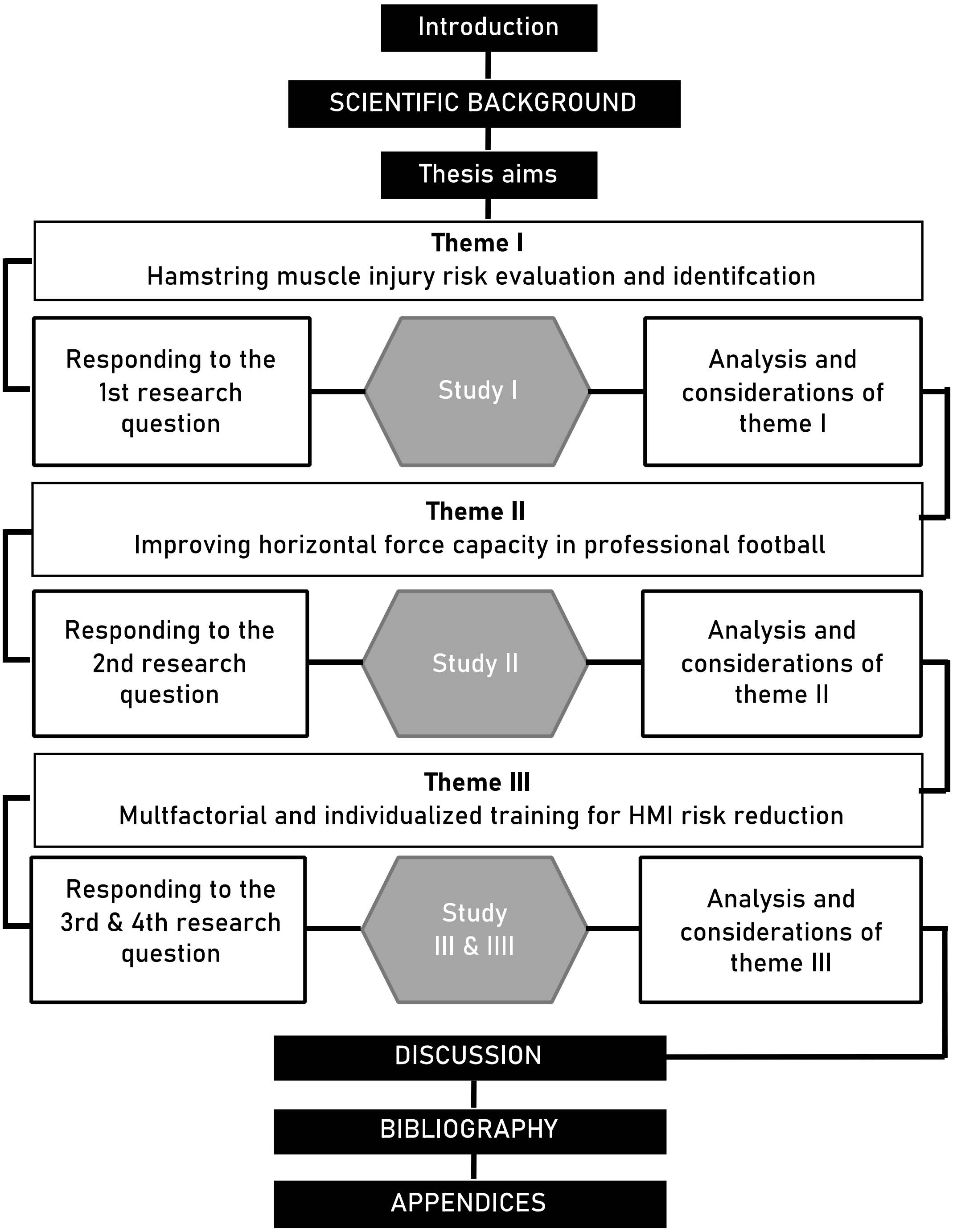

Figure 1. Thesis structure

1.6. GENERAL INTRODUCTION

The high frequency of hamstring muscle injuries (HMI) and the corresponding difficulty of their reduction continues to create uncertainty in professional football (Ekstrand *et al.*, 2016; Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Van der Horst, Thorborg and Opar, 2020; Tabben *et al.*, 2021). Recent evidence indicates they place the largest injury burden in professional football (Ekstrand *et al.*, 2016; Tabben *et al.*, 2021), which is calculated as a combination of injury incidence and severity (Bahr, Clarsen and Ekstrand, 2018). Unfortunately, previous HMI is also one of the most consistent risk factors for future HMI (Green *et al.*, 2020; Pizzari, Green and van Dyk, 2020). Consequently, an athlete who sustains an injury can fall into a vicious cycle of physical and emotional distress, and lose playing time – all of which place a large financial burden on the clubs (Hickey *et al.*, 2014). Hamstring injury rates have shown to increase during the last decades (Ekstrand *et al.*, 2016), mostly taking place during sprinting (Woods *et al.*, 2004; Ekstrand *et al.*, 2012). Some evidence suggests that this is caused by parallel increases in game speed (Haugen, Tønnessen and Seiler, 2013) and sprint volume (Barnes *et al.*, 2014). The biomechanical reasoning for higher speeds being a potential risk factor has to do with the hamstring's mechanical role in sprinting. The hamstring muscle groups morphology and excitation have been numerously associated with sprint performance (Morin *et al.*, 2015; Bellinger *et al.*, 2021; Nuell *et al.*, 2021). Therefore, as football is a sprint-based team sport, it makes sense that an increase in speed demands increases the hamstrings workload. This biomechanical hypothesis has been supported by musculoskeletal modelling studies (Chumanov, Heiderscheit and Thelen, 2007, 2011; Dorn, Schache and Pandy, 2012; Pandy *et al.*, 2021). There, it has been shown that the relationship between increased velocity and the corresponding increase in hamstring muscle forces seems to be exponential (Chumanov, Heiderscheit and Thelen, 2011; Dorn, Schache and Pandy, 2012).

Continuously increased efforts to reduce HMI have been set to motion during the last decades. This includes researching the HMI risk factors that are considered important in football, HMI mechanisms, introducing and commencing new HMI risk reduction strategies, and re-evaluating the epidemiological situation (Askling, Karlsson and Thorstensson, 2003; Woods *et al.*, 2004; Petersen *et al.*, 2011; Ekstrand *et al.*, 2012; Ekstrand *et al.*, 2016; Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Pizzari, Green and van Dyk, 2020; Van der Horst, Thorborg and Opar, 2020). The risk factors that have been commonly found include both extrinsic and intrinsic components (Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Pizzari, Green and van

Dyk, 2020). Furthermore, intrinsic and extrinsic components are divided into modifiable and non-modifiable categories (Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Pizzari, Green and van Dyk, 2020). Although all categories are of interest, modifiable intrinsic risk factors are of the highest importance from an interventional perspective. Despite numerous variables have been assessed, strong evidence for specific risk factors is typically lacking (Pizzari, Green and van Dyk, 2020). Furthermore, multiple proposed risk factors have yet to be explored on a construct validity scale. There is a consensus for HMI risk being a multifactorial problem, i.e., no single modifiable variable can predict injury risk (Ayala *et al.*, 2019; Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Pizzari, Green and van Dyk, 2020; Opar *et al.*, 2021). The most researched areas within football cohorts include injury history, strength, and range of motion components (Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020). Within these areas of interest, the most researched risk factors include previous HMI (Arnason *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2006; Hauge Engebretsen *et al.*, 2010; Fousekis *et al.*, 2011; Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016; Lee *et al.*, 2018; Shalaj *et al.*, 2020), eccentric knee flexor strength (Dauty *et al.*, 2016; Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016; Lee *et al.*, 2018; Ayala *et al.*, 2019; Shalaj *et al.*, 2020), and knee extension/straight leg raise flexibility (Bradley and Portas, 2007; Henderson, Barnes and Portas, 2010; Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017; van Doormaal *et al.*, 2017; van Dyk, Farooq, *et al.*, 2018). The non-modifiable intrinsic risk factor of previous HMI has the strongest level of evidence (Pizzari, Green and van Dyk, 2020), while intrinsic modifiable eccentric knee flexor strength and hamstring range of motion includes multiple supporting and contradicting publications or supporting evidence with low clinical significance (Fousekis *et al.*, 2011; Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016; Lee *et al.*, 2018; van Dyk, Farooq, *et al.*, 2018; Opar *et al.*, 2021). Two larger methodological limitations may partially explain why consistent risk factors have not been found: 1) Controlling for the multifactorial nature of HMI (Ayala *et al.*, 2019), and 2) the seasonal changes in variables of interest (Dauty *et al.*, 2016; Moreno-Pérez *et al.*, 2020). Naturally, these are difficult to control since multifactorial testing can be highly time consuming (especially if repeated during the season), expensive, requires a broad skill set from the practitioners (i.e., operation of gold-standard devices), and therefore can be met with skepticism in high level settings. Balancing these factors, while maintaining evidence-based practices, is imperative to conduct high quality testing in football clubs with different constraints.

Furthermore, the appropriate scope of multifactorial testing is still not evident. This includes discussions of which specific tests should be included, such as strength, range of motion, or other less researched categories. Although still limited in supporting evidence, efforts have been made to conduct more practical testing to the context of HMI by measuring biomechanical variables during sprinting (Mendiguchia *et al.*, 2014; Mendiguchia *et al.*, 2016; Alizadeh and Mattes, 2019; Edouard, Lahti *et al.*, 2021). This includes assessing macroscopic (mechanical output) and more microscopic (i.e., sprint "technique") biomechanical variables during sprinting (Mendiguchia *et al.*, 2014; Mendiguchia *et al.*, 2016; Alizadeh and Mattes, 2019; Edouard, Lahti, *et al.*, 2021). In terms of the macroscopic, low levels of maximal theoretical horizontal force (F*0*) derived from a sprint force-velocity profile has been recently shown to be associated with increased HMI risk within different levels of football (Edouard, Lahti, *et al.*, 2021). Furthermore, the measurement of F*0* has been recently made highly accessible via a validated field method (Samozino *et al.*, 2016; Romero-Franco *et al.*, 2017; Morin *et al.*, 2019). The relevance of measuring F*0* is based on the logic that the hamstring muscle group have been mostly associated with the horizontal component of the ground reaction force vector (Jacobs and van Ingen Schenau, 1992; Fukashiro *et al.*, 2005; Morin *et al.*, 2015). Therefore, testing horizontal force output during sprinting may give a practical view of the hamstrings health status in their contribution to sprinting acceleration when they are working as part of a system. Since sprinting performance relies on the ability to produce force horizontally throughout the sprint (Morin et al. 2011, Rabita et al. 2015), this creates an opportunity for simultaneous performance and risk assessment applicable to the sport. Furthermore, F*0* is a 'macroscopic' measure, and does not account for the degrees of freedom over which force can be produced. This partially explains the resurgence of research concerning sprint technique among football players (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Alizadeh and Mattes, 2019). In addition to modelling studies showing the influence of trunk-pelvis motion on hamstring strain (Chumanov, Heiderscheit and Thelen, 2007; Higashihara, Nagano and Takahashi, 2017), two prospective pilot studies have associated lumbo-pelvic control elements such as anterior pelvic tilt (APT) and thoracic lateral movement with increased HMI risk in team sports (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Kenneally-Dabrowski *et al.*, 2019). Therefore, efforts should be made in finding solutions to increase accessibility (i.e., overcoming practical constraints) to the aforementioned testing categories and whether their results might be consolidated to improve risk assessment.

Thereafter, interventions should be conducted to see whether the proposed modifiable intrinsic risk factors can be realistically manipulated within the constraints of football environments.

Finally, the influence of their manipulation on HMI rates should be verified. Eccentric knee flexor strength is the only training category that has successfully been manipulated in high level football settings and shown to reduce HMI risk (Askling *et al.*, 2003; Croisier *et al.*, 2008; Van Dyk, Behan and Whiteley, 2019). While more research is needed in general, isolating modifiable variables within a randomized format is understandably challenging in high-level settings. Multiple qualitative studies indicate that professional teams use varying multifactorial strategies to reduce HMI risk (McCall, Dupont and Ekstrand, 2016; Meurer, Silva and Baroni, 2017). This renders studies with control groups ethically ambiguous, since a control group might be required to forgo parts of current active protocols that may place them at higher injury risk. Although being at a lower level of scientific evidence than randomized controlled trial, prospective cohort studies might be a valid and practical alternative, where specific multifactorial programs are updated from one season to another and corresponding changes in HMI rates are monitored (Arnason *et al.*, 2008; Suarez-Arrones *et al.*, 2021). Furthermore, individualization of multifactorial programs are promising (Mendiguchia *et al.*, 2017; Suarez-Arrones *et al.*, 2021), which requires players be trained to some extent based on (previously screened) individual training needs within each category of interest. Individualization may be more effective in training outcomes, use of time, and even psychologically more motivating for players (Suarez-Arrones *et al.*, 2021).

As such, we would likely benefit of exploring whether multifactorial hamstring testing can be made more accessible, whether the test scores are related to HMI risk, and whether its use in guiding HMI risk reduction training can contribute to reducing injury rates in professional level settings. Secondly, whether F*0* can be modified in a professional setting may be relevant for HMI risk reduction and performance enhancement and requires exploration.

2. SCIENTIFIC BACKGROUND

2.1. THE SPORT OF FOOTBALL

2.1.1. OVERVIEW

Football, also known as soccer, is the world's most popular sport with approximately 270 million registered participants reported by 204 International Federation of Association Football (FIFA) member national associations (FIFA, 2007). There are approximately 130 000 registered professional players around the world (FIFA, 2019). Football is a team sport played with a spherical ball between two teams of 11 players. A standard adult football match consists of two 45-min halves, interspaced usually by a 15-min break. The dimensions of a typical field for international adult matches is ~100–110 m long and ~64–75 m wide (FIFA, 2015).

2.1.2. NEEDS ANALYSIS OF FOOTBALL

Football is an intermittent sport, including low- (standing to walking) and high-intensity (running to sprinting) activities (Bloomfield, Polman and O'Donoghue, 2007). It involves multiple motor skills, such as sprinting, changing direction, ball-specific skills (e.g., dribbling and kicking), jumping, and player-on-player contact (Dalen *et al.*, 2016). Performance in football depends on a variety of individual skills and the interaction among different players within the team. Technical and tactical skills are of central importance, with pass completion, frequency of forward and total passes, balls received and average touches per possession being higher among successful versus less successful teams (Bradley *et al.*, 2013; Haugen *et al.*, 2014). However, players from successful teams also display superior physical capacities which highlights the necessity for aptitude along specific physiological and neuromuscular abilities (Cometti *et al.*, 2001; Haugen, Tønnessen and Seiler, 2013; Tønnessen *et al.*, 2013). The most distinguishable physical properties seem to be associated with sprint performance, including peak velocity and early acceleration qualities (0-20 m) (Cometti *et al.*, 2001; Haugen, Tønnessen and Seiler, 2013). In fact, while traditionally considered a sport reliant on aerobic capacity, elite or professional players become faster over time while aerobic fitness has plateaued or even decreased slightly (Haugen, Tønnessen and Seiler, 2013; Tønnessen *et al.*, 2013).

In male football, outfield players cover 9 to 12 km during a match, which approximately 8 % to 12 % is high-intensity running or sprinting (Burgess, Naughton and Norton, 2006; Di Salvo *et al.*, 2007; Rampinini, Bishop, *et al.*, 2007; Rampinini, Coutts, *et al.*, 2007; Vigne *et al.*, 2010).

The number of high-intensity sprints per match ranges between 17 to 81, with the vast majority being under 20 m with a mean duration of two to four seconds (Burgess, Naughton and Norton, 2006; Di Salvo *et al.*, 2007; Vigne *et al.*, 2010). Reported peak sprint-velocity values among football players are 31 to 35 km/h (Rampinini, Bishop, *et al.*, 2007; Rampinini, Coutts, *et al.*, 2007; Mendez-Villanueva *et al.*, 2011), with the upper bounds of that range (i.e., around 10 m/s) comparable to moderate-level track and field sprinter. Even though the capacity to accelerate quickly in multiple directions is considered essential in football, the importance of linear sprinting speed seems to be one of the most important base structures. Faude, Koch, & Meyer (2012) reported that in the German national league, the scoring player performed a linear sprint before almost half of all analyzed goals. Interestingly, these linear sprints were performed mostly without an opponent or the ball, and linear sprinting was also the most predominant action for the assisting player (mostly conducted with the ball) (Faude, Koch and Meyer, 2012).

2.2. INJURIES IN PROFESSIONAL MALE FOOTBALL

2.2.1. OVERVIEW

Injury-related publications within football have increased exponentially since the early 2000's (Figure 2). This shows a proof of interest in evaluating the injury burden and the possible etiology of injuries, with around 40 articles per year addressing the topic. Trends and relationships between teams with less injuries and acquiring a better league standing have been observed (Arnason *et al.*, 2004; Hägglund *et al.*, 2013). The financial cost of first-team players in European football sustaining 1 month injury has been estimated at ~ €500,000 (Ekstrand, 2013). Furthermore, players returning to sport after injury may display reduced performance for extended periods (Barth *et al.*, 2019). Therefore, there is a clear incentive to reduce the risk of injuries in football.

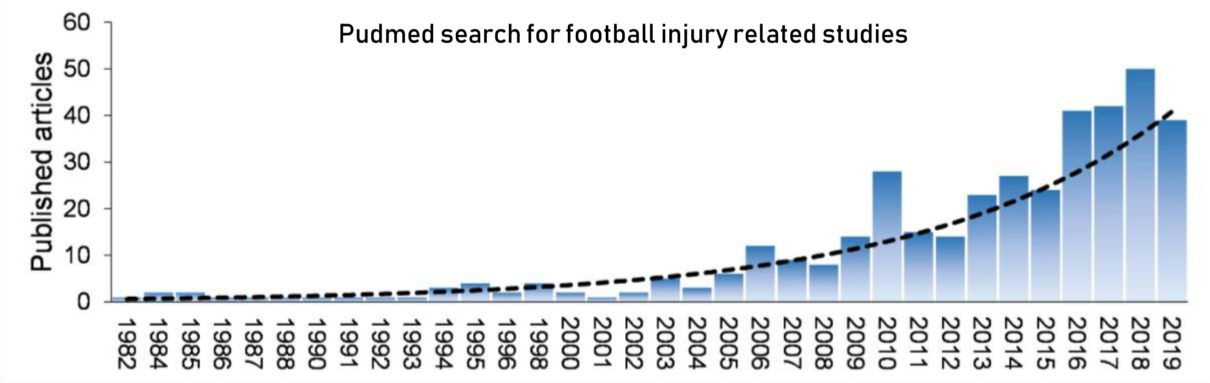

Figure 2. The change in research interest within football during the last four decades.

2.2.2. INJURY OVERVIEW

An injury is usually defined in professional football by ‘time-loss’, which is any physical complaint suffered by a player that takes place from participating in football and leads to the player being unable to fully participate in future football training sessions or matches (Ekstrand *et al.*, 2011). Usually, injury risk is expressed as incidence, which is the number of new cases of an injury in a specific population during a given time. Injury incidence is commonly reported as the number of injuries per 1000 hours of player exposure to football. Recently, there has been emphasis on reporting injury burden alongside incidence, which is the number of days absent per 1000 hours of player exposure due to injury in football (Bahr, Clarsen and Ekstrand, 2018); this has been added so that practitioners can be aware of both frequency and severity of the injury within the same statistic (Figure 3).

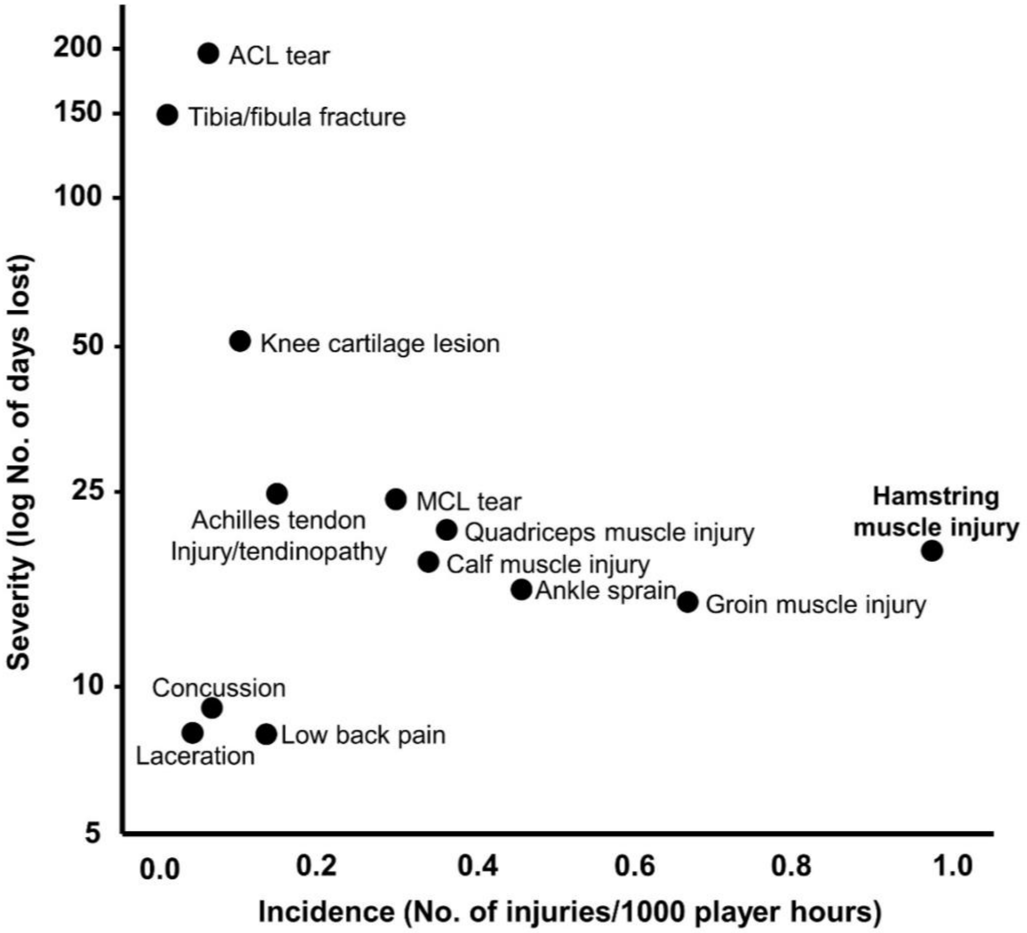

Figure 3. Injury severity and its corresponding incidence levels in professional male football (Bahr, Clarsen and Ekstrand, 2018).

The health outcomes from playing professional football can seem bleak. Studies have shown that 65% to 91% of the players will sustain at least one time-loss injury during a season (Arnason *et al.*, 2004; Waldén, Hägglund and Ekstrand, 2005; Lüthje *et al.*, 2007; Ekstrand *et al.*, 2016). Injury incidence rates of 8.7–26.6 per 1000 match hours and 1.4–4.0 per 1000 training hours have been reported in male professional football (Ekstrand *et al.*, 2011; Hägglund *et al.*, 2013; Bjørneboe, Bahr and Andersen, 2014). The number of injury days absent per 1000 hours (i.e., injury burden) has been reported to be around 18 (Ekstrand *et al.*, 2013). Approximately 14 % of player rosters are regularly unavailable for matches due to injuries (Ekstrand *et al.*, 2013). To provide perspective in respect to viewing football as a career, industrial workers (e.g., factory workers) have only 0.02 injuries per 1000 hours which is ~1000 times lower than football players (Drawer and Fuller, 2002). A consistent finding is that the risk of sustaining an injury is around 6 to 8 times higher in matches compared to training (Ekstrand *et al.*, 2011; Hägglund *et al.*, 2013; Bjørneboe, Bahr and Andersen, 2014). Furthermore, the injury incidence during matches appears higher in professional football compared to lower play levels (Anne-Marie van Beijsterveldt *et al.*, 2015). This may be linked to competitiveness, where greater winning rewards lead to higher exertion and consequently increased injury risk (Wong and Hong, 2005). Match injuries appear to have increased in professional Norwegian football between 2002 and 2007 (Bjørneboe, Bahr and Andersen, 2014). However, this finding has not been consistent within other cohorts, with UEFA teams during 2001 to 2008 and the Swedish professional league 1982 to 2001 showing no change (Hagglund, Walden and Ekstrand, 2003; Ekstrand, Hägglund and Waldén, 2011).

The most common injury location in professional football is the lower-body, with the thigh, groin, knee and ankle accounting for 50 to 70 % of injuries (Ekstrand, Hägglund and Waldén, 2011; Ekstrand *et al.*, 2013). The most common types of injuries are muscle injuries, followed by sprain/ligament injuries, contusions, and tendon injuries, which account for around 80 % of injuries (Ekstrand, Hägglund, and Waldén 2011). In a very recent prospective injury monitoring study, which is one of the largest to date in professional football (3302 players, 11820 injuries), while sprain/ligament injury rates have decreased, rates of muscle injuries have remained constant (Ekstrand *et al.*, 2021). This is congruent with previous reports (Ekstrand *et al.*, 2013). Non-contact injuries are the most common, with around 20% occurring during sprinting (Wong and Hong, 2005).

Reinjuries also contribute substantially to total injury incidence and burden. A reinjury is defined as an injury of the same type and at the same location as the initial injury, occurring no more than two months after a player's return to full participation from the initial injury (Ekstrand *et al.*, 2013). Out of all injuries in professional football, 12 to 20 % are reinjuries (Ekstrand *et al.*, 2011; Bjørneboe, Bahr and Andersen, 2014), with muscle injuries being predominant in these statistics (Bjørneboe, Bahr and Andersen, 2014). Ekstrand, Hägglund, and Waldén (2011) found that 16 % of the muscle injuries were reinjuries and lead to 30 % longer absences compared to the initial rehabilitation period. Furthermore, players with a previous HMI, groin injury, and knee joint trauma have been found to have a two to three times higher likelihood of suffering an identical injury in the following season (Hägglund, Waldén and Ekstrand, 2006).

2.2.3. HAMSTRING INJURIES IN PROFESSIONAL MALE FOOTBALL

HMI are considered one of the most common injuries in football, with 12-16 % of all injuries (Woods *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2005; Ekstrand *et al.*, 2011, 2012; Stubbe *et al.*, 2015; Shalaj *et al.*, 2016), and are consistently reported as the most frequent muscle injury (Witvrouw *et al.*, 2003; Fousekis *et al.*, 2011; Ekstrand *et al.*, 2013; Tabben *et al.*, 2021). Hamstring injury incidence rates of 1.54 - 4.77 injuries per 1000 match hours and 0.25 to 0.51 injuries per 1000 training hours have been reported in male professional football, corresponding to a six to ten times higher risk during matches (Bjørneboe, Bahr and Andersen, 2014; Ekstrand *et al.*, 2016). The total HMI njury incidence rate has been reported to be 1 to 1.20 injuries per 1000 exposure hours (Ekstrand *et al.*, 2011; Bjørneboe, Bahr and Andersen, 2014; Ekstrand *et al.*, 2016). The incidence of HMI appears to have maintained or slightly increased over the last decades (Ekstrand *et al.,* 2016). HMI tend to also have the highest injury burden (13.2 to 19.7 absent days per 1000 hours football exposure) (Ekstrand *et al.*, 2011, 2013; Ekstrand *et al,*. 2016; Tabben *et al.*, 2021). This is due to that HMI have both a relatively high frequency (including re-injuries) and a high amount of average days lost from sport, corresponding to an average rehabilitation timeline of 14 to 19 days (Ekstrand *et al.*, 2011, 2013; Ekstrand, Waldén, Hägglund, 2016; Tabben *et al.*, 2021).

In surveying the occurrence of HMI, Woods et al. (2004) reported that of the 749 injuries observed nearly half occurred during the last third of the first and second halves of the match. The majority of all HMI (50 to 70 %) take place during sprinting (Woods *et al.*, 2004; Ekstrand *et al.*, 2012), with no significant difference in severity (Ekstrand *et al.*, 2012). Other injury mechanisms included overuse and overstretching/slide tackling (5 %), shooting (4 %), change of direction (4 %), passing (2 %), and jumping (2 %).

The gold-standard grading of HMI is based on MRI from a scale of 0 to 3, where 0 is least and 3 most severe, respectively (Table 1). The most typical severity of HMI are grade 1 or 2, which represent 80 % of injuries (Ekstrand *et al.*, 2012). Players with grade 0 HMI returned to sport after 8 (± 3) days; after grade 1 injures 17 (± 10) days, after grade 2 injuries 22 (± 11) days, and after grade 3 injuries 73 (± 60) days (Ekstrand *et al.*, 2012).

Table 1. Radiological grading of hamstring injury (Ekstrand *et al.*, 2012).

Grade 0	Negative MRI without any visible pathology
Grade 1	Edema but no architectural distortion
Grade 2	Architectural disruption indicating partial tear
Grade 3	Total muscle or tendon rupture

In professional-level sprint-based team sports, the biceps femoris long head (BFlh) is overwhelmingly the most injured hamstring muscle, with over 80 % of injuries affecting its tissue (Koulouris *et al.*, 2007; Ekstrand *et al.*, 2012; Wangensteen *et al.*, 2016) (Figure 4). Semimembranosus (SM) has been shown to have an injury rate of 5.3 to 11 %, while not far behind the semitendinosus (ST) has shown to have an injury rate of 5.3 to 6.5 % (Ekstrand *et al.*, 2012).

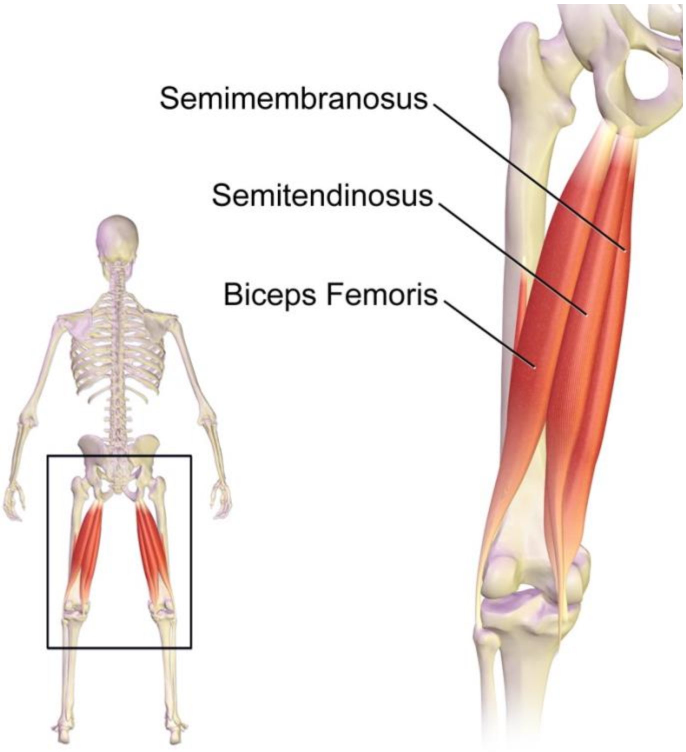

Figure 4. Simple view of the hamstring muscles.

Sometimes a clear distinction is difficult, as the tissue damage can take place between muscles, possibly most typically between the BFlh and the ST (Wangensteen *et al.*, 2016). Ekstrand et al. (2012a) showed that rehabilitation time was not different between the muscles and that all reinjuries in their cohort (n=30) happened to the BFlh. A recent finding demonstrated that injuries to the dominant leg have been structurally more serious (Svensson *et al.*, 2018). According to Ekstrand, Hägglund, and Waldén (2011), in a team of 25 players, approximately four to six HMI (including reinjuries) occur during the season, which collectively represent ~80 missed days, and 14 missed matches.

HMI's have not always been as common in professional football. According to prospective injury studies from the 1980's, the ankle sprain was the most common injury, followed by knee sprain, with hamstring injuries being less frequent (Ekstrand and Gillquist, 1983; Nielsen and Yde, 1989; Ekstrand and Tropp, 1990; Engstrom *et al.*, 1990; Poulsen *et al.*, 1991). In modern football, there seems to be a shift towards an increased representation of muscle injury, typically to the hamstrings and groin, and these are now more common than joint sprains (Hawkins and Fuller, 1999; Hawkins *et al.*, 2001; Arnason *et al.*, 2004; Waldén, Hägglund and Ekstrand, 2005; Ekstrand *et al*., 2016). Ekstrand *et al*., (2016) reported a yearly increase of 4 % in HMI between 2001 and 2014. The increase in muscle injuries, including HMI, has been suggested as a by-product of increases in sprinting speed and sprinting volume within football (Hägglund, 2007). As most HMI take place during sprinting, where hamstring energy absorption requirements increase substantially with increasing speed (Chumanov, Heiderscheit and Thelen, 2007, 2011), it is logical that a faster game with increased sprint load could lead to unprecedented challenges. This is further supported by evidence from track and field where HMI burden tends to be higher in disciplines with higher gait speeds (Edouard, Hollander, *et al.*, 2021). Recently, the "faster game" hypothesis has gained support, with professional football players shown to sprint faster (Haugen, Tønnessen and Seiler, 2013), and sprint volume having increased in matches (Barnes *et al.*, 2014). Haugen, Tønnessen, and Seiler (2013) tested 939 professional Norwegian football players between 1995 and 2010, and reported that players from 2006 to 2010 had significantly faster 0 to 20 m split-times and peak velocities than players from the 1995 to 1999 and 2000 to 2005 epochs. Barnes et al. (2014) compared the physical and technical performance differences between the 2006/2007 and 2012/2013 English Premier League seasons and demonstrated that there was a 35 % increase in sprint distance and frequency.

Reinjuries are a serious problem within HMI management. In addition to being one of the most common injuries in professional football, the hamstring muscles are also one of the most common reinjury sites (Ekstrand *et al.*, 2011). Furthermore, data from 12 European countries indicate a 2 % increase in hamstring muscle reinjuries between 2001 to 2014 (Ekstrand *et al.*, 2016). Injury reporting of early reinjuries differs slightly, as those taking place within a span of 2 months of the index injury or within the next 1 to 2 seasons. The largest studies show that early and late hamstring muscle reinjury rates in professional football range between 12 to 16 % (Woods *et al.*, 2004; Ekstrand *et al.*, 2012; Ekstrand *et al.*, 2016). A recent study showed that 50 % of the 19 MRI confirmed reinjuries occurred within the first 50 days after the index injury, corresponding to 25 days after return to sport (RTS) (Wangensteen *et al.*, 2016). Furthermore, 70 % of reinjuries occurred within the first 100 days (Wangensteen *et al.*, 2016). Therefore, although the reinjury risk remains high for a substantially longer period than the first months, most reinjuries occur early after the index injury and RTS. These reinjuries also have been reported to increase the rehabilitation length and thus time away from the sport (Ekstrand *et al.*, 2011; Ekstrand, Hägglund and Waldén, 2011). Furthermore, reinjury risk seems higher when the BFlh was the index injury (Ekstrand *et al.*, 2012; Wangensteen *et al.*, 2016).

2.3. A BRIEF “DIVE” INTO HAMSTRING MUSCLE ANATOMY AND FUNCTION

2.3.1. OVERVIEW

There are three muscles of the hamstring muscle group, the biceps femoris (BF), semitendinosus (ST), and semimembranosus (SM) (Figure 5). The BF muscle is further divided into a long head (BFlh) and a short head (BFsh). The BFlh, ST, and SM are biarticular muscles originating from the ischial tuberosity and spanning across the hip and knee joints. The primary role of these biarticular hamstring muscles is to function as a hip extensor and knee flexor. The biarticular hamstring muscles are innervated by the tibial division of the sciatic nerve. The BFsh originates from the linea aspera, is innervated by the common fibular (peroneal) division of the sciatic nerve and is the only mono-articular hamstring muscle. It crosses the knee joint, and, therefore, has a primarily function as a knee flexor. When the knee is partially flexed, the biarticular hamstring muscles assist in internal (SM and ST) and external (BFlh and BFsh) rotation of the lower leg (Silder *et al.*, 2008).

The mechanical properties of a muscle-tendon unit (MTU) are largely determined by its physiological properties. As such, structural and architectural differences found between the hamstring MTUs suggest more specific mechanical functions among them (Delp and Zajac, 1992). This in return directly influences fundamental mechanical properties, such the expression of force capability per unit of length and at different velocities (Kellis, 2018) (Table 2).

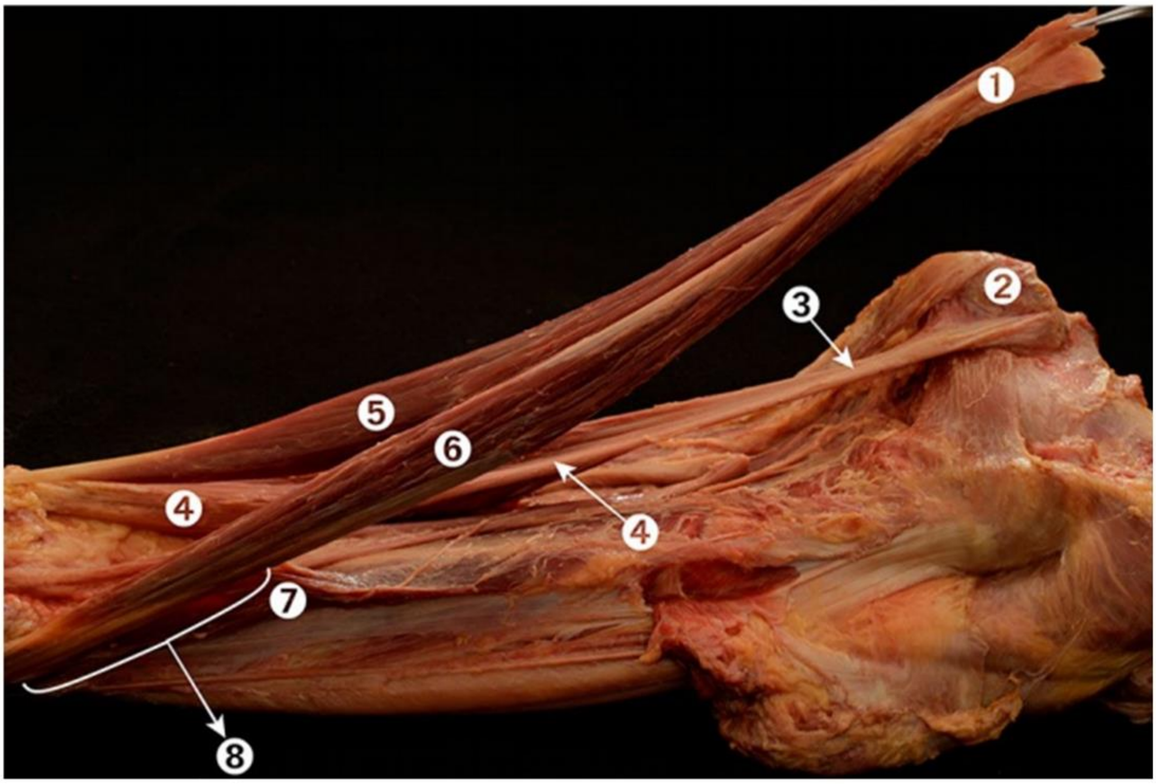

Figure 5. Posterolateral view of the hamstrings. (1) Conjoined tendon of the semitendinosus and the long head of the BF; (2) ischial tuberosity; (3) proximal tendon of the SM muscle; (4) SM muscle; (5) ST muscle; (6) long head of the BF muscle; (7) short head of the BF muscle; (8) conjoined tendon of the long and the short head of the BF (Stępień et al., 2019).

2.3.2. FUNCTIONAL ANATOMY OF THE HAMSTRING MUSCLES

To reflect their function, the hamstring muscles can be divided into medial and lateral heads, with the medial hamstring muscles (ST and SM) running medially and attaching to the tibia and the lateral hamstring muscles (BFlh and BFsh) running laterally and attaching mainly to the fibula (Table 2). This compartmental divide is not just based on attachments points but on functional anatomical "pairs". Within each pair there is one muscle designed for excursion and another muscle designed for force production. Specifically, the BFlh and SM have a greater physiological cross-sectional area (PCSA) and pennation angle, which makes their force generation capacity larger than the ST and BFsh (Kellis *et al.*, 2012; Kellis, 2018). In contrast, the ST and BFsh have almost a double the fascicle to muscle length ratio (FL/ML), which results in greater length-change capacity (Woodley and Mercer, 2005; Kellis *et al.*, 2012). Furthermore, the ST capacity for excursion is also supported by its longest free tendon at the distal end (van der Made et al. 2015; Woodley and Mercer 2005), which is associated with more tendon compliance (Kellis, 2018). Specifically, BFlh and SM muscle tissue experience larger changes in tension or relative fiber length compared to the ST when the hip is moved into flexion or the knee into extension (Kumazaki, Ehara and Sakai, 2012; Nakamura *et al.*, 2016).

Table 2. Structural and architecture details of the hamstring muscles.

Variable*	Lateral hamstring pair		Medial hamstring pair	
	Biceps femoris LH	Biceps Femoris SH	Semimembranosus	Semitendinosus
Proximal MTJ tendon length (% of muscle length)	35 - 47 %	-	47 %	27 - 28 %
Proximal free tendon length (% of muscle length)	12 - 15 %	-	24 - 25 %	0.4 - 3 %
Distal MTJ tendon length (% of muscle length)	41 %	37 %	39 - 44 %	26 - 32 %
Distal free tendon length (% of muscle length)	21 - 22 %	2 %	14 – 16 %	25 - 30 %
Total tendon (% of muscle length)	124 %	39 %	132 %	87 %
Fiber type (Range)	MHC-I: 47.1 % (32.6 - 71.0) MHC-IIA: 35.5 % (21.5 - 60.0) MHC-IIX: 17.4 % (0.0 - 30.9)			
PSCA relative to each other	2nd	4th	1st	3rd
Force generation range (relative to each other)	Moderate	Low	Moderate	High
Pennation angle (°)	13.7	12.4	17.9	7.81

Fascicle length (mm)	8.71	10.4	6.49	15.6
MTU length (cm)	36.9	22.9	33.2	36.8
FL/ML ratio	Lower excursion capacity	Higher excursion capacity	Lower excursion capacity	Higher excursion capacity

* = Data included in the table is based on Kellis *et al.*, 2012; Evangelidis *et al.*, 2016; Avrillon *et al.*, 2018; and Kellis, 2018

Based on hamstring muscle simulations by Kellis *et al.*, (2012), the ST contributes the most force at long lengths, BFlh and SM provide up to 70 % of force production at intermediate lengths, and BFsh provides the largest force at short length (Figure 6). This potentially confirms the proposition that muscles within synergistic groups may vary their architecture to produce forces with large size, range, and velocity characteristics (Lieber and Fridén, 2000; Kellis, 2018).

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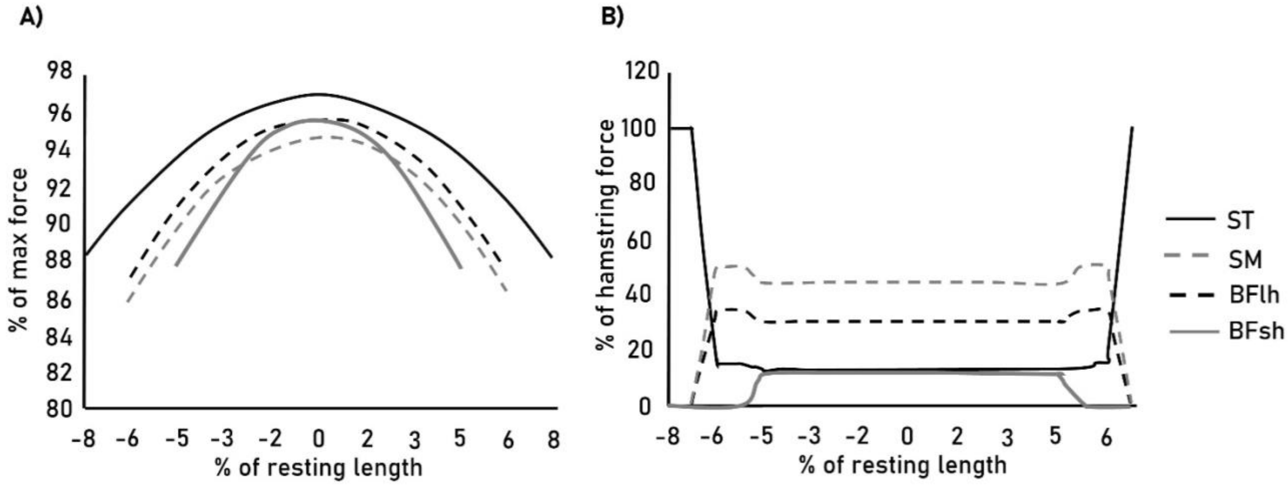

Figure 6. Length change and the corresponding force change in different heads of the hamstrings. (A) Kellis *et al*., 2012 produced a planimetric model of the semitendinosus (ST), semimembranosus (SM), biceps femoris long head (BFlh) and short head (BFsh) based on their cadavers. Assumptions that were made in the model included that the muscles force–length relationship is parabolic, that the data represent values at optimal length, that all muscles reach optimal length at the same length and that architecture does not vary along muscle length. All muscles were permitted to shorten 15 % of their resting length. Total force of the hamstring muscles was estimated by summing individual muscle forces after modifying for their PCSA. (B) Relative force contribution by each individual hamstring muscle when shortened by 15 %.

Traditionally, the hamstring muscles have been considered a muscle specializing in speed, which was based on initial evidence of a dominant fast twitch composition (Garrett, Califf and Bassett, 1984). However, these muscle fiber composition data were based on 10 cadavers of elderly individuals, which may not represent in vivo measurements of younger individuals. The fast twitch theory was later partially debunked by Evangelidis *et al.,* (2016), who reported a more balanced muscle fiber composition in the BFlh among 31 healthy young men. However, it should be mentioned that the range of slow and fast fiber compositions between individuals was high (Evangelidis *et al.*, 2017) (Table 2). Therefore, specific individuals may present a larger fast twitch composition, which may be due to training background and/or genetics.

2.4. HAMSTRING FUNCTION DURING SPRINTING AND INJURY MECHANISM

2.4.1. OVERVIEW

This chapter will focus on the biarticular hamstring muscles, as BFsh is rarely injured. Furthermore, as there is little biomechanical data available on injuries taking place in other scenarios (stretching/slide tackling, shooting, change of direction, passing, and jumping), this chapter will focus on describing the most common HMI mechanism: sprinting.

2.4.2. HAMSTRING FUNCTION AND INJURY MECHANISM DURING SPRINTING

To understand the typical injury mechanism, one must first consider the role of the hamstring muscles in sprinting. The hamstring muscles neuromuscular function and physiology has been repeatedly associated with sprint performance (Morin *et al.*, 2015; Bellinger *et al.*, 2021; Miller *et al.*, 2021; Nuell *et al.*, 2021; Takahashi, Kamibayashi and Wakahara, 2021). Specifically, the hamstring muscles appear to specialize in the horizontal force component of the ground reaction force vector (GRF), which is responsible for forward propulsion of center of mass (Hamner and Delp, 2013; Morin *et al.*, 2015; Pandy *et al.*, 2021). In this central role, the hamstring muscle complex deals with the result of both high motion dependent torques (e.g., open chain based forces: interia, coriolis, and centrifugal forces) and contact torques (e.g., closed chain force from ground reaction forces) (Zhong *et al.*, 2017). The way in which the hamstrings function to propel us forward is arguably highly interesting. As the hamstring muscles contract, they create both a hip extension moment and a knee flexion moment. Intuitively it would seem that contracting the hamstring muscles during lower limb extension at the point of ground contact would be counterproductive for another lower limb extensor, i.e., their antagonist the quadriceps. However, when the leg hits the ground during sprinting, the knee flexion moment created by the hamstrings cannot create dynamic knee flexion due to static friction of the ground. To overcome this, the body rotates over the fixed point (i.e., the lower leg), referred to in physics as stiction (Ertelt and Gronwald, 2019). In turn, the sprinters center of mass rotates over the fixed point with the help of the hamstring muscles, which become a temporary knee extensor (Figure 7). In this manner, the hamstrings efficiently transfer energy from the knee to the hip (Jacobs and van Ingen Schenau, 1992; Pandy *et al.*, 2021). This partially supports their design for involvement in forward propulsion and contributing to the horizontal component of the GRF vector.

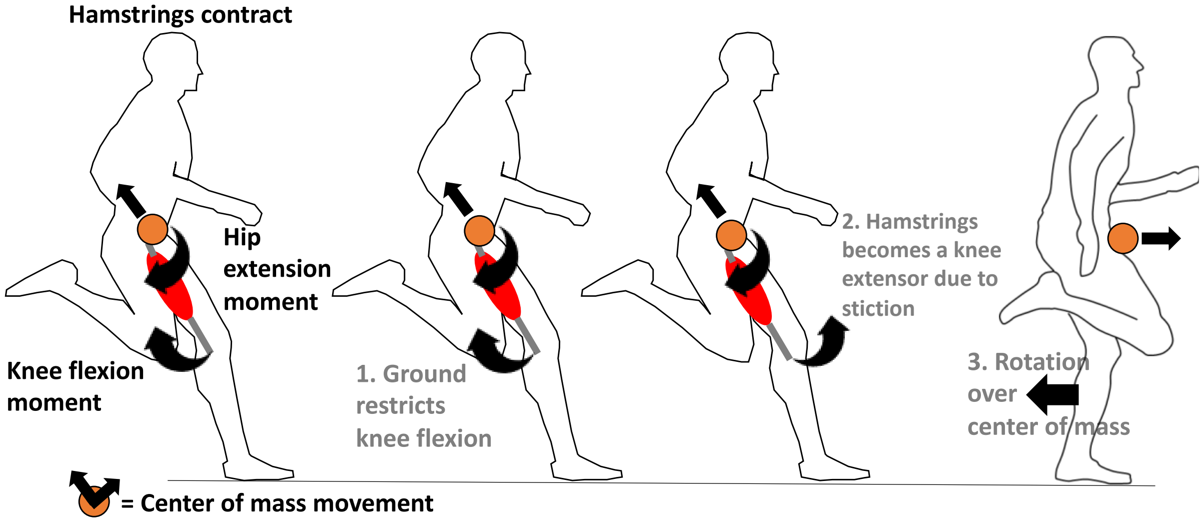

Figure 7. Hamstrings function during sprinting.

Although direct (in vivo) analysis of hamstring muscle kinetics during sprinting has not been achieved, both inverse dynamics and musculoskeletal modelling approaches can yield macroscopic estimates (Martin *et al.*, 2018). Studies adopting these approaches have helped us infer where and how in the sprint cycle injuries likely occur (Chumanov, Heiderscheit and Thelen, 2007, 2011; Dorn, Schache and Pandy, 2012; Schache *et al.*, 2012). However, it is still unknown whether this can be isolated to a single event, or may be better explained by repeated trauma that exceeds the hamstrings extensibility and contractile properties (Huygaerts, Cos, Cohen, *et al.*, 2020; Baumert *et al.*, 2021). One important question is whether hamstring muscle tears can be attributed to strain of the active muscle tissue, and to what degree the experienced forces play a role irrespective of muscle lengthening. Our current understanding is that most injuries occur during the late swing phase of the sprint cycle, followed by the early stance phase (Kenneally-Dabrowski *et al.*, 2019). The late swing phase takes place around 60% of the swing phase or around 90 % of the gait cycle, which begins as the hip reaches maximal flexion and terminates at foot strike (Thelen, Chumanov, Hoerth, *et al.*, 2005; Schache *et al.*, 2013). At this point of the sprint cycle, modelling indicates that the hamstring MTU's are lengthening, and at extremely high velocities (Chumanov, Heiderscheit and Thelen, 2011; Schache *et al.*, 2012, 2013). Lengthening is defined as the MTU moving outside of optimal length (i.e., the length or angle at which peak torque occurs), also defined as MTU strain (Wan *et al.*, 2017b). Importantly, MTU lengthening does not define whether the muscle or tendon is lengthening, but rather indicates a net lengthening of the MTU complex. The BFlh's MTU has been shown to experience the most lengthening during maximal sprinting, followed by the SM and finally the ST (Schache *et al.*, 2013). The differences in MTU length change between the hamstring muscles can be attributed to differences in the influence of hip and knee movement to each individual hamstring muscle. The lower limb is roughly at 120-130 degrees of hip flexion and 140-150 degrees of knee flexion during the late swing phase (Figure 8, C).

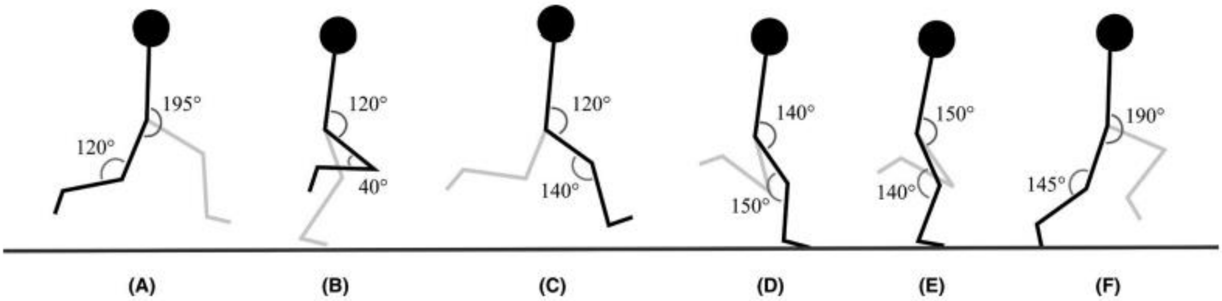

Figure 8. Phases from the sprint cycle. Presented by Kenneally-Dabrowski et al. (2019). A) Early swing, B) Mid-swing, C) Late swing, D) Early stance/foot strike, E), Mid-stance, F), Late stance/toe-off.

At this point, BFlh lengthening at the hip is equal to the ST and more than the SM. At the knee the BFlh, ST and SM shorten to comparable magnitudes (Thelen, Chumanov, Hoerth, *et al.*, 2005). Thus, the net effect is that the largest length change takes place in BFlh, which might explain the increased strain injury sensitivity of the BFlh during sprinting (Thelen, Chumanov, Best, *et al.*, 2005; Schache *et al.*, 2010). The degree of MTU strain during sprinting has likely been exaggerated in numerous modelling studies due to calculating the hamstring muscles optimal length based on the participants hamstring length in a standing position instead of directly assessing each subjects peak angle of torque (Wan *et al.*, 2017a; Ruan, 2018). Recent studies controlling for this limitation show that movement (6-10%) is still evident outside of optimal MTU length (Wan *et al.*, 2017b; Wan *et al.*, 2020).

As the hamstring muscle excitation (peak electromyography) peakes during late swing phase (Hegyi, Gonçalves, *et al.*, 2019), it can be considered an active MTU lengthening, therefore an eccentric contraction at the level of the MTU (Figure 9, B).

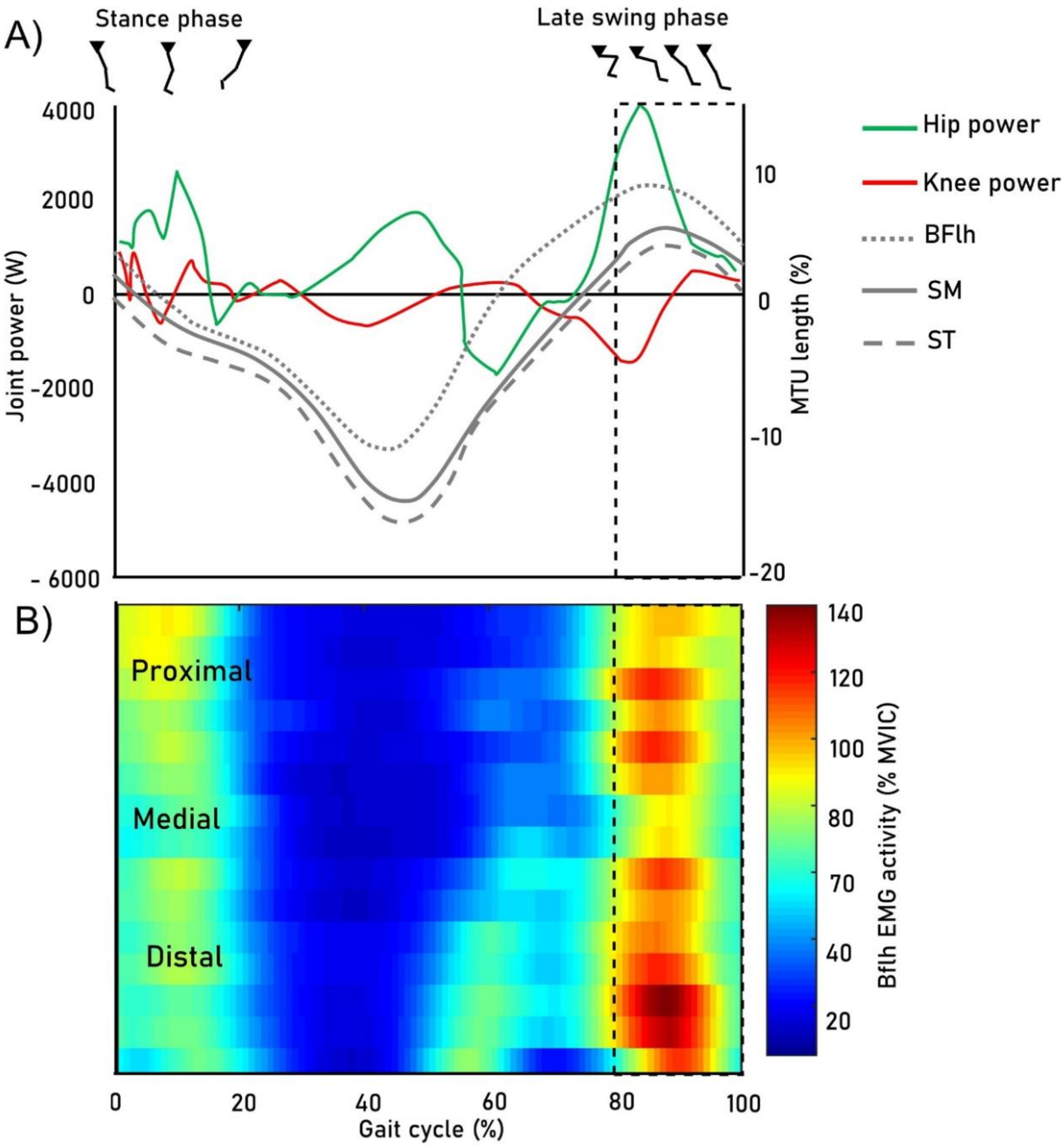

Figure 9. Sprint kinetics and the change in length and excitation of the hamstrings. A) Hip and knee joint powers during the sprint cycle from Zhong *et al.,* (2017) combined with hamstring MTU length data from Schache *et al*., (2013). B) Proximal to distal BFlh EMG activity during the sprint cycle from Hegyi *et al*., (2019). Black dashed box represents the late swing phase. Based on these studies we can see that the hamstrings workload leaks during active lengthening at the point of the late swing phase.

This likely means that during the late swing phase, the hamstring muscles maximize energy absorption to propel the runner forward via an open chain stretch-shortening cycle (SSC) (Dorn, Schache and Pandy, 2012). However, although there is a net lengthening of the hamstring MTU, it is simultaneously contracting concentrically at the level of the hip while contracting eccentrically at the level of the knee (Figure 9, A). In essence, during the late swing phase, the hamstring muscles assist in driving the hip towards the ground while actively resisting the rapid angular acceleration of the knee joint into extension (Dorn, Schache and Pandy, 2012). Modelling confirms that the hamstring muscles reach their peak force requirements during these events, followed by a second smaller peak reached during initial stance (Thelen, Chumanov, Best, *et al.*, 2005). Modelling data also indicate the peak normalized forces experienced during late swing phase are approximately 20.3, 32.9, and 6.43 N.kg^{-1} for BFlh, SM, and ST, respectively (Table 3). This corresponds to an average distribution of 34 %, 55 %, and 12 % for BFlh, SM, and ST, respectively. This distribution represents the physiological cross-sectional area (PCSA) distribution typically found between the biarticular hamstring muscles (Table 2). Importantly, these ratios are not from elite sprint populations where distributions may differ (Miller *et al.*, 2021). As the lower limb velocities are maximized during the late swing phase, it is also the point of peak mechanical power at both the hip and knee joint (Zhong *et al.*, 2017). This would infer that the hamstrings MTU are reaching their peak mechanical workload simultaneously at the knee and hip while it is actively lengthened outside of optimal length.

Table 3. Hamstring muscle forces during the late swing and early stance phase.

Variable*	BFlh	SM	ST
Peak forces normalized to body-mass during late swing phase and distribution, N.kg^{-1} (%)	20.3 (34)	32.9 (55)	6.43 (12)
Peak forces normalized to body-mass during early stance and distribution, N.kg^{-1} (%)	8.11 (29)	9.29 (36)	4.92 (20)

* = Data summarized from (Thelen, Chumanov, Best, *et al.*, 2005; Chumanov, Heiderscheit and Thelen, 2007; Schache *et al.*, 2012; Nagano *et al.*, 2014)

Although the late swing is considered the main phase associated with muscle injuries, initial contact is a close second (Kenneally-Dabrowski *et al.*, 2019). The opposing forces provided by ground reaction forces can reach 3 to 4 x body mass (Nagahara, Kanehisa and Fukunaga, 2020). Furthermore, concerns exist regarding over filtering of force data during early stance phase (Kenneally-Dabrowski *et al.*, 2019). Here large ground reaction force spikes take place, during an extremely short (~0.04 s) and highly variable phase (Bezodis, Salo and Trewartha, 2013), which can result in mischaracterization. Unlike the late swing phase, the hamstring MTU is shortening during initial contact (Schache *et al.*, 2012), which should change the injury mechanism. This quick change from an eccentric to concentric knee flexion torque action has been discussed to increase fragility of the hamstrings (Alonso *et al.*, 2012).

As discussed, modelling studies demonstrate evidence that the hamstrings MTU are actively lengthening during peak force requirements. However, in-vivo hamstrings active and passive tissue length changes are still unknown and continue to be debated. One question is whether the hamstring muscle fascicles are rotating towards the line of pull (i.e., the tendon) during MTU lengthening instead of lengthening at the sarcomere level (Van Hooren and Bosch, 2018). This rotation, also termed architectural gear ratio, appears to occur in pennate-type muscles during high-intensity SSC activities (Azizi and Roberts, 2014). Larger pennation angles lead to larger rotation, which might decrease the chance of eccentric muscle lengthening (Hollville *et al.*, 2019). This phenomenon is biomechanically logical both from a metabolic and performance perspective. For example, SSC fatigue increases active lengthening of the muscle tissue (Nicol, Avela and Komi, 2006). As the hamstrings vary in pennation angle both at an intermuscular and between-individual level (Kellis, 2018; Huygaerts, Cos, Cohen, *et al.*, 2020), a variety of sensitivities to different contraction types are plausible between hamstring muscles. For example, the most injured hamstring muscle (i.e., the BFlh) is considered only moderately pennate, at least compared to the semimembranosus muscle (Kellis, 2018). According to architectural muscle gearing, this increases its likelihood of eccentric lengthening during SSC activities (Huygaerts, Cos, Daniel D. Cohen, *et al.*, 2020). Thus, although it is unclear whether an active muscle lengthening of the BFlh is typical during sprinting, it remains plausible that sprinting based BFlh injuries occur during active lengthening.

2.5. HAMSTRING RISK FACTORS

2.5.1. OVERVIEW

More efficient injury intervention requires better understanding the injury occurrence, for example by identifying the injury risk factors and mechanisms at play. Substantial research exists within hamstring muscle injuries in football, with the many proposed risk factors typically generally divided into extrinsic and intrinsic categories (Figure 10) (Bahr and Krosshaug, 2005). Extrinsic and intrinsic risk factors can be additionally categorized as non-modifiable or modifiable. Extrinsic risk factors can be compromised of modifiable and non-modifiable variables. Modifiable extrinsic variables can be such things as sport exposure, playing position, sports equipment, and playing environment. A non-modifiable extrinsic variable can be weather (Green *et al.*, 2020). Intrinsic factors are focused on internal factors and can be also divided into modifiable and non-modifiable categories. Non-modifiable intrinsic risk factors include variables that cannot be changed such as age, gender, and injury history. Modifiable intrinsic risk factors can be influenced with interventions, which include such variables as range of motion, fitness, strength, sleeping habits, nutrition, and potentially even psychological factors. Certain intrinsic risk factors are likely important to consider for all football injuries, such as the factors presented in Figure 10 by Bahr and Krosshaug (2005). However, more specific factors per injury should also be considered to improve risk identification approaches in football (Buckthorpe *et al.*, 2019).

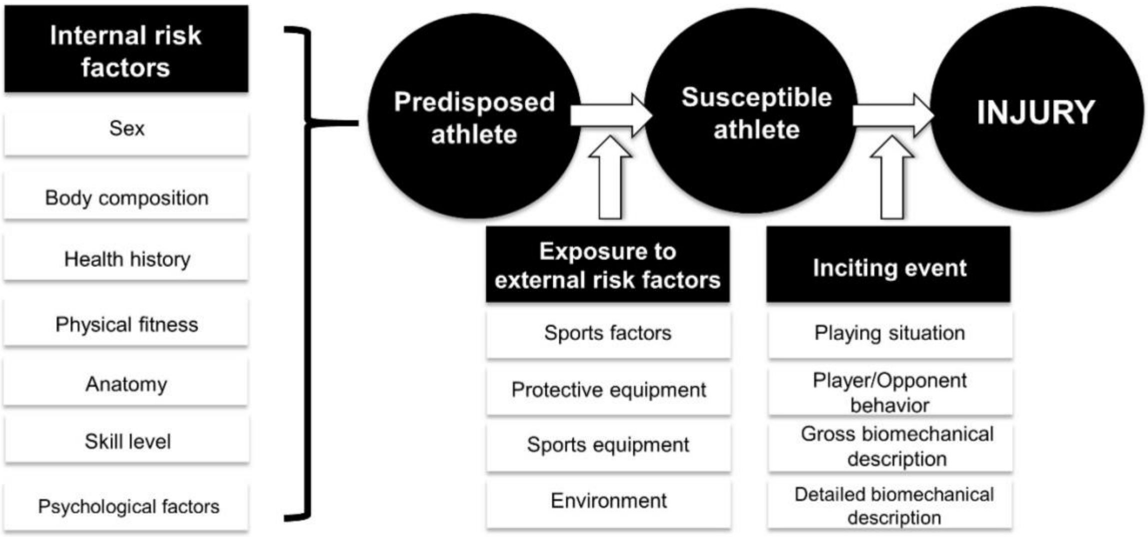

Figure 10. Adapted version of the comprehensive model for injury causation by Bahr and Krosshaug (2005).

2.5.2. TEAM SPORT INJURY RISK MODELS

During the last decades different models have been published to provide a guideline for progressive stages in approaching unresolved injury related problems in sport (van Mechelen, Hlobil and Kemper, 1992; Finch, 2006; Roe *et al.*, 2017; O'Brien *et al.*, 2019). The most up-to-date model is the Team-sport Injury Prevention model, or "TIP" (O'Brien *et al.*, 2019), presented in Figure 11. All the models share commonalities, however the TIP model aimed to further reflected the everyday injury risk reduction approaches of sports medicine and sports science staff working in professional football teams (O'Brien *et al.*, 2019). The TIP model aims to mirror the cyclical nature of real-world injury risk reduction process, which requires ongoing evaluation and adaptation of risk reduction strategies, as opposed to a simplified linear step-by-step process (O'Brien *et al.*, 2019).

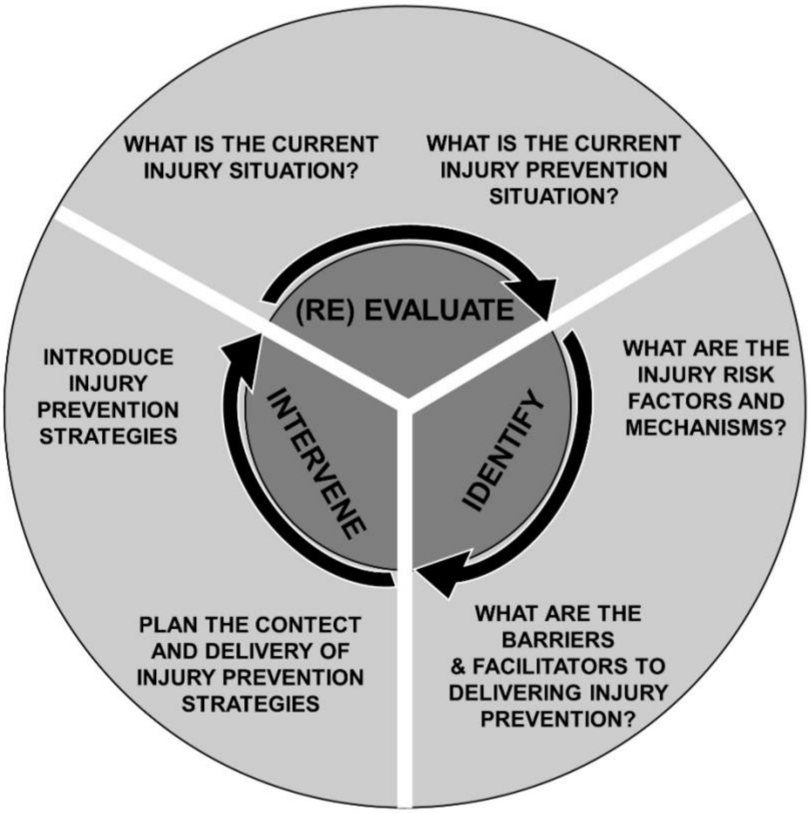

Figure 11. Team-sport Injury Prevention model ("TIP" model) presented by O'Brien et al. (2019)

The first stage primarily involves analyzing what injuries can be expected or asking: "what is the problem?". In this step typical injuries are identified, including incidence, severity ratings (how serious they are), reoccurrence rates, and when does the injury usually take place (first vs.

second half, match vs training, different times of the season etc.). The second question in the first stage involves asking: “what is the injury risk reduction situation?”. This involves analyzing which injury reduction strategies are currently being used or ignored and the reasons why. The second stage involves identifying the injury etiology, (i.e., the risk factors and mechanisms for injury), and centers on answering “why are the players getting injured?”. In this stage it is important not to underestimate the multifactorial nature of injuries (Bittencourt *et al.*, 2016), assess injury risk at an individual player level (Roe *et al.*, 2017), and consider to what degree risk factors can be modified (O’Brien *et al.*, 2019). Furthermore, the second stage relies on an understanding of the physical requirements of the sport (Roe *et al.*, 2017). The first two stages are mainly completed via epidemiological prospective cohort studies in comparable level teams. Optimally, a multivariable statistical approach should be adopted to account for the multifactorial nature of injury and the ideally the training participation (Bahr and Holme, 2003). The third stage relies on the insight gained from those preceding it, and includes planning and implementing risk reduction measures. Modifiable intrinsic risk factors are emphasized, and typically include implementing training interventions aiming to reduce risk. Within a research context, this is ideally done through a randomized controlled trial (RCT). However, this is highly unrealistic in professional football, as to fulfill the RCT design teams would likely need to postpone certain ongoing risk reduction strategies, and thus take on high performance and financial in the name of research. Although not as scientifically rigorous, prospective cohort studies, where two seasons are compared in a non-randomized manner, also provide valuable information if potential seasonal differences are controlled for (Arnason *et al.*, 2008). The risk reduction strategies that can be implemented will be influenced by the team’s current situation, implementation barriers for potential risk factors, currently published injury risk reduction research and the team staff members’ previous field experiences (O’Brien *et al.*, 2019). As an example, ultrasound (US) analysis has been used to successfully identify players at risk for HMI in conjugation with strength testing (Timmins, Bourne, *et al.*, 2016). However, accurate US is expensive, time consuming and requires a highly skilled operator to use reliably (Franchi *et al.*, 2020; Sarto *et al.*, 2021). Therefore, research should be designed to consider the realistic practical barriers faced by teams in the aim of maximized dissemination of information on preventive measures. Finally, the last stage evaluating the situation, or re-evaluating (i.e., going back to stage 1). This is where the success of the risk reduction measure is assessed.

2.5.3. EXTRINSIC RISK FACTORS FOR HAMSTRING MUSCLE INJURY

In sprint-based team sports, studies have investigated whether exposure to the sport or playing environment increases injury risk. Many of thes factors are non-modifiable in the short-term (field conditions, shoe technology, rules of the game and structure of the league, etc). Weather is also included as an extrinsic risk factor. Currently the most important extrinsic risk factor for HMI appears to be sudden increases in high-speed sprinting volume (Pizzari, Green and van Dyk, 2020). This has only been examined in one football cohort (Malone, Owen, *et al.*, 2018), while not specifically looking at HMI but lower-limb injuries as a whole. However, this finding has been reproduced in other team-sports with high-levels of HMI (Duhig *et al.*, 2016; Malone, Roe, Doran, Gabbett and Collins, 2017a; Colby *et al.*, 2018). Thus, it would be unlikely that the HMI risk would not be influenced. The source for sudden increases in high-speed sprinting and the difficulty of avoiding them have been discussed in literature. As higher sprint velocities may be achieved in matches compared to football training, and match schedules can be highly congested in football, it can be difficult to control for sudden workload spikes (Hägglund *et al.*, 2013).

However, another reproduced finding within high-speed sprinting risk factor studies has been exposure to frequent high-speed sprints during the week and reduced injury risk (Malone, Roe, Doran, Gabbett and Collins, 2017a; Colby *et al.*, 2018; Malone, Owen, *et al.*, 2018). Low weekly exposure to high-speed sprints increased the risk of injury (Malone, Roe, Doran, Gabbett and K. D. Collins, 2017a; Colby *et al.*, 2018; Malone, Owen, *et al.*, 2018). Furthermore, Malone *et al.*, (2017a) study among elite Gaelic football players found that players sprinting >95 % of maximal velocity at least once during weekly training had a lower risk of injury compared to the reference group of 85 % maximal velocity. They discussed the presence of a U-shaped optimal stimuli curve, where under- and over-exposure were associated with higher injury risk (Malone, Roe, Doran, Gabbett and Collins, 2017a). However, the direct relationship of appropriate high-speed sprinting exposure in a football context and its relationship to HMI still needs to be examined.

Playing position has shown to be a significant extrinsic risk factor, with goalkeepers showing a large reduced risk of injury in multiple cohort studies (Woods *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2013; van Dyk, Bahr, *et al.*, 2018). Given the clear disparity in playing tasks, this difference is clearly attributed to the reduced sprint demands of this position. The influence of ethnicity is arguably a sensitive subject to research. Nonetheless, one of the largest analyses on professional football injuries showed that players of black origin had an increased risk for HMI (p=0.05) (Woods *et al.*, 2004). While no other football-centric studies have examined ethnicity as a variable, other sprint-based team sports have shown ethnic background influences injury risk (Verrall *et al.*, 2001). Ethnicity has been thought to affect the HMI risk due different biomechanical properties. In the example of black players possessing higher injury risk, some theories include higher degree of anterior pelvic tilt (APT) and a larger proportion of fast twitch fibers (Woods *et al.*, 2004). However, recently it has been shown that when controlling for body-mass, aerobic capacity, and player position in a multivariable analysis, ethnicity was no longer a risk factor in Australian football players (Gastin *et al.*, 2015). Although not completed in a football cohort, this shows the importance of controlling for confounding factors (Pizzari, Green and van Dyk, 2020).

2.5.4. NON-MODIFIABLE INTRINSIC RISK FACTORS FOR HAMSTRING MUSCLE INJURY

The intrinsic non-modifiable risk factors most frequently associated with increased HMI risk in football are age and previous HMI (Bisciotti *et al.*, 2020). Age and previous HMI are also the most tested risk factors in HMI literature, which have been included in both univariable and multivariable statistical testing. Other less studied non-modifiable risk factors include other injuries, playing position, and ethnicity.

2.5.4.1. Previous HMI as a risk factor

To our knowledge, all football related risk factor studies using multivariable statistical models have identified previous HMI as a significant risk factor for future HMI (Arnason *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2006; Hauge Engebretsen *et al.*, 2010; Fousekis *et al.*, 2011; Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016; Lee *et al.*, 2018; Shalaj *et al.*, 2020). These results are mostly consistent with the outcome of the univariable analyses, with only some studies showing no association (Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2017; van Dyk, Bahr, *et al.*, 2018). However, clear trends are present in some univariable models, with Timmins, Bourne *et al.*, (2016) results indicating a p-value of 0.06 for increased risk of previous HMI. A recent meta-analysis by Green *et al.*, (2020) in team sport athletes demonstrated that previous HMI during the last two seasons inflates HMI risk by 270 % ($p < 0.001$), further increasing to 480 % if the injury was within the same season ($p < 0.001$). Wangensteen *et al.*, (2016) showed that this risk is especially high during the first 4 weeks after return to sport in team sports. Previously injured hamstring muscles appear to reduce strength, range of motion, fascicle length, voluntary activation, stretch-reflexes, tendon reflexes, increase atrophy, and scar tissue (Silder *et al.*, 2008; Sanfilippo *et al.*, 2013; Maniar *et al.*, 2016; Timmins, Shield, *et al.*, 2016). Reinjuries are likely primarily attributed to inadequate rehabilitation or premature return to play after the initial injury (Hägglund, Waldén and Ekstrand, 2006; Mendiguchia *et al.*, 2014). However, some injuries may increase the risk of reinjury irrespective of time interval. This may be due to residual deficits in the previously injured joint or muscle(s) that leave the player more vulnerable to re-injury (Hägglund, Waldén and Ekstrand, 2006).

2.5.4.2. Age as a risk factor

Of seven risk factor studies using multivariable statistical models in football cohorts, five reported associations between risk and age (Arnason *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2006; Henderson, Barnes and Portas, 2010; Timmins, Bourne, *et al.*, 2016; Shalaj *et al.*, 2020). The interesting question is whether there is a dependent relationship between age and previous injury. The two studies that did not show an association for age in a multivariable analysis did show an association in a univariable analysis (Hauge Engebretsen *et al.*, 2010; Lee *et al.*, 2018). Furthermore, the same studies showed that previous HMI was a risk factor in both a univariable- and multivariable analysis (Hauge Engebretsen *et al.*, 2010; Lee *et al.*, 2018). This potentially indicates that in some football populations, age is no longer a strong independent risk factor, unlike previous HMI. This is logical as with increasing age, there is a larger likelihood that an player has a previous injuries simply due to greater accrued time in the sport. However, this is not always the case as some populations seem to show some independence between the two risk factors (Arnason *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2006; Timmins, Bourne, *et al.*, 2016; Shalaj *et al.*, 2020). One explanation might be that athletic properties decline with age, such as of strength, and mechanical power (Kostka, 2005; Faulkner *et al.*, 2008), and consequently older players might have difficulty to keep up with sporting demands (i.e., higher injury risk). However, research concerning these changes and how they interact with HMI are lacking.

2.5.4.3. Other non-modifiable risk factors

Other less robust or unclear risk factors include other lower leg injuries, and ethnicity. Unfortunately, few studies assess these qualities within football cohorts. A recent meta-analysis by Green *et al.*, (2020) in team sports revealed that there was a 70% increase of HMI risk if the player had a previous anterior cruciate ligament (ACL) injury. One potential reason for the increased HMI risk may be reduced knee proprioception and strength leading to increased instability during gait (Katayama *et al.*, 2004; Tashman *et al.*, 2004; Abourezk *et al.*, 2017). Recent evidence suggests that when ST tendon autograft is used as the graft for ACL reconstruction (ACLR), reduced ST muscle mass and activation during eccentric contractions may remain an issue for up to 6 years post-surgery (Messer *et al.*, 2020). ST muscle deficits may in turn distribute a larger workload to the other hamstrings. This phenomenon has recently been shown possible in football players with a history of ACLR using ST tendon autograft (Tampere *et al.*, 2021). Tampere *et al.*, (2021) showed that after fatiguing eccentric contractions, football players with ACLR had significantly higher exercise-related activity in the BF muscle and significantly lower activity in the ST muscle after fatiguing eccentric contractions compared to control.

Green *et al*., (2020) also showed that a previous calf injury increased the HMI risk by 50 %. The gastrocnemius calf muscle, which is also a knee flexor, has been shown to contribute to a small degree in absorbing energy in form of an eccentric MTU contraction during the late swing phase (Schache *et al.*, 2010). Thus, lacking calf muscle function may lead to the hamstring muscles taking an even higher workload during the late swing phase. Previous ankle injuries have been shown to increase the likelihood of HMI in track & field sprinters (Malliaropoulos *et al.*, 2018), which supports the importance of having adequate proprioception at adjacent joints. However, there is a complete lack of studies assessing for these issues in football cohorts. Despite the lack of studies, knee and ankle ligament injuries followed by triceps surae injuries are highly common in football (Arnason *et al.*, 2004; Ekstrand, Hägglund and Waldén, 2011; Tabben *et al.*, 2021). In any case, residual negative effects could logically occur, irrespective of sport.

2.5.5. MODIFIABLE INTRINSIC RISK FACTORS FOR HMI

There are numerous researched modifiable HMI intrinsic risk factors in football. The most typical factors in football are related to strength levels, joint range of motion, muscle architecture, and motor control, respectively (Buckthorpe *et al.*, 2019; Green *et al.*, 2020). These factors, or highly similar ones, have been proposed as risk factors within sports science literature spanning nearly four decades (Agre, 1985). However, a lot of uncertainty and unanswered questions remain on what factors are important and constant innovation in testing procedures seems to be present. Similar methodological challenges are found for modifiable intrinsic risk factor as non-modifiable. These include accounting for the multifactorial nature of HMI, including interactions between modifiable and non-modifiable factors, and as such literature within the topic can be potentially easily misinterpreted (Ayala *et al.*, 2019).

2.5.5.1. Maximal strength levels as a risk factor

To date, strength levels are the most researched HMI risk factor in all sprint-based team sports. The aim with measuring strength is to gain an understanding of the hamstrings capacity to tolerate forces in higher injury risk scenarios. Traditionally, the definition of strength testing tends to bias towards assessment of maximal voluntary isometric force (MVIC). Although HMI risk related strength assessment is usually completed by isolating the knee joint, literature includes numerous different knee joint assessment approaches. In football cohorts, knee flexor strength has been measured in different contraction forms (isokinetic, isoinertial), modes (eccentric, concentric, isometric), velocities (30-300 °/s), including different angles, and ratios (asymmetries between limbs and between the agonist and antagonist) (Dauty *et al.*, 2016; Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2017; Dauty, Menu and Fouasson-Chailloux, 2018).

The most researched strength related HMI risk factors associated with increased HMI risk in football have been eccentric knee flexor strength (Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016; Lee *et al.*, 2018; Ayala *et al.*, 2019; Shalaj *et al.*, 2020), between-limb strength asymmetries (Croisier *et al.*, 2008; Fousekis *et al.*, 2011; Van Dyk *et al.*, 2017; Lee *et al.*, 2018), and Hamstring:Quadriceps (H :Q) ratios (Croisier *et al.*, 2008; Dauty *et al.*, 2016; Lee *et al.*, 2018; Ayala *et al.*, 2019). The rationale behind each of these variables are mostly sprint related. As the hamstring MTU contracts eccentrically at the level of the knee during the late swing phase to decelerate concentric knee extension (Chumanov, Heiderscheit and Thelen, 2007;

Schache *et al.*, 2014; Zhong *et al.*, 2017), it is logical that eccentric contractions and antagonist strength ratios (H:Q ratio) are of interest. As sprinting is a unilateral activity, maximal strength asymmetries draw attention. Furthermore, retrospective evidence exists for some of these variables, showing that players with a history of HMI can exhibit deficits in eccentric strength (Opar *et al.*, 2013). However, contradicting evidence exists for each of these variables in their association with increased HMI risk, including statistically 'clear' models ($p < 0.05$) but with low clinical value (Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2016, 2017; Dauty, Menu and Fouasson-Chailloux, 2018; Lee *et al.*, 2018; Opar *et al.*, 2021), rendering outcomes for practitioners confusing. Some contradictions could be attributed to different testing forms, lacking testing specificity, or a lack of controlling for confounding factors with more advanced statistical models. For example, between-limb strength asymmetries increased HMI risk in two studies when tested eccentrically in an isokinetic device (Croisier *et al.*, 2008; Fousekis *et al.*, 2011). However, two other studies (Timmins, Bourne, *et al.*, 2016; Van Dyk *et al.*, 2017) that tested limb asymmetries eccentrically via the bilateral Nordic hamstring exercise found no associations. It should be also mentioned that Croisier et al. (2008) used a multi-criteria approach, which included other asymmetry measures in the same model, making it difficult to isolate which type of asymmetry measure is essential. Furthermore, although there is a consensus on the importance of eccentric strength (Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020; Pizzari, Green and van Dyk, 2020), injured and uninjured populations can overlap substantially (Van Dyk *et al.*, 2016, 2017; Dauty, Menu and Fouasson-Chailloux, 2018; Opar *et al.*, 2021). This demonstrates that no individual strength variable seems to be sustainably of clinical value on an individual level (Ruddy *et al.*, 2019). A recent study supported this notion by showing moderate to high accuracy in predicting HMI risk using a more complex statistical model (Ayala *et al.*, 2019), however, more studies are needed.

2.5.5.2. Hamstring muscle architecture

An innovative approach to measuring hamstring muscle architecture and associated HMI risk has gained popularity in recent years: fascicle length. The measurement of fascicle length in HMI literature started to gain traction when previously injured hamstring limbs were found to have substantial deficits in angle of peak torque (Brockett, Morgan and Proske, 2004). This meant that compared to the non-injured limb, the injured limb exhibited peak torque (i.e., optimal length) at shorter lengths (Figure 12).

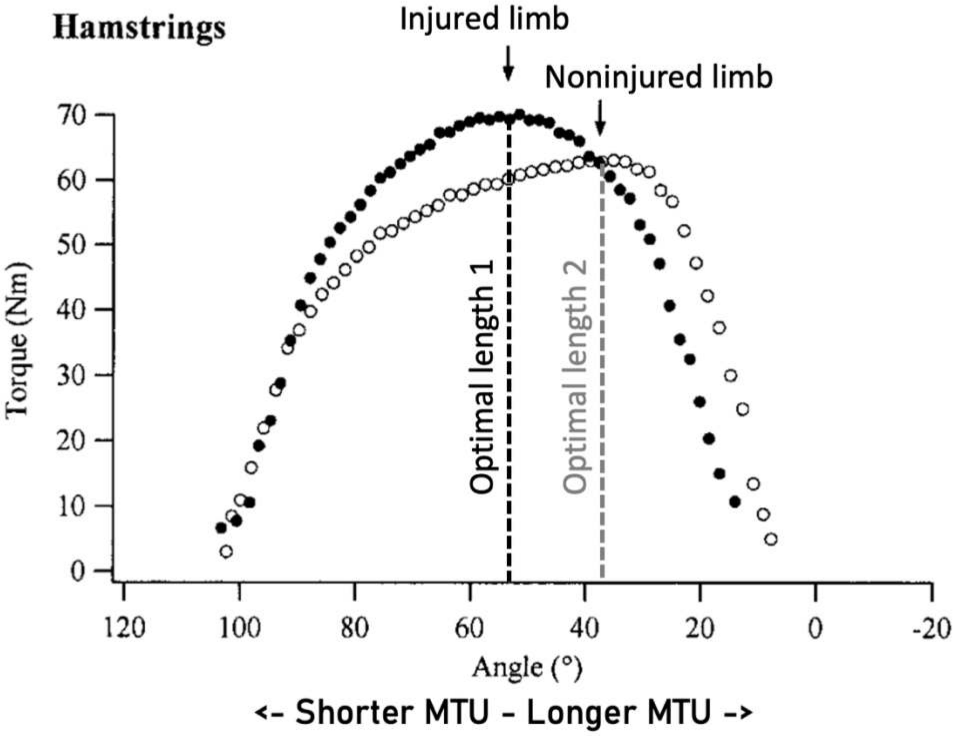

Figure 12. Eccentric knee flexor angle-torque curves of a subject with a previous HMI (black dots) vs non-injured limb (open dots). The previously injured HMI has its optimal length (1) at shorter MTU lengths compared to the non-injured limb (2). This result in turn-initiated interest in what structural changes at the level of the muscle may explain this. The Figure is adapted from Brockett, Morgan and Proske (2004).

As discussed earlier, MTU strain is defined as MTU lengthening past optimal length (Wan *et al.*, 2017b). Therefore, a hamstring MTU with reduced optimal length could have an increased likelihood of damage from eccentric actions that include different degrees of MTU strain, such as sprinting. This is especially true for BFlh, which is both the most injured hamstring muscle and the most variable in length during sprinting (Schache *et al.*, 2013). Brockett, Morgan, and Proske (2004) proposed that reduced optimal length may especially be a potential risk factor for reinjury. The reduction in optimal length was hypothesized to be due to decreases in sarcomeres in series (Brockett, Morgan and Proske, 2004), although there is recent evidence to suggest that shorter sarcomeres instead of reduced sarcomeres in series should also be considered (Pincheira *et al.*, 2021). In turn, this could narrow the MTU's length-tension relationship, consequently reducing force at longer lengths (Lieber and Ward, 2011). The 'sarcomere' theory was later tested indirectly and retrospectively via assessing fascicle length in previously injured BFlh muscles via two-dimensional ultrasonography (Timmins *et al.*, 2015). Using this approach, Timmins *et al.*, (2015) showed that fascicle length relative to muscle thickness was less in the injured compared to the uninjured limb, showing initial indirect support to the reduced sarcomere theory. The following year, shorter BFlh fascicle length was shown for the first time to be associated with increased risk for index HMI in a football cohort by the same research group (Timmins, Bourne, *et al.*, 2016). Interestingly, fascicle length was found to be an independent risk factor in tandem to absolute eccentric strength. Furthermore, Timmins, Bourne, *et al.*, (2016) observed that both increased fascicle length and eccentric strength reduced the risk of reinjury and likelihood of injury with increasing age. Although the accuracy of the ultrasound method employed by Timmins, Bourne, *et al.*, (2016) has gained criticism (Franchi *et al.*, 2020; Huygaerts, Cos, Cohen, *et al.*, 2020), a wide range of evidence exists that hamstring muscle fascicle length can be increased with eccentric strength training (Bourne *et al.*, 2017), and that eccentric training is important to consider for HMI risk reduction (Van Dyk, Behan and Whiteley, 2019). Recently, fascicle length has been even shown to increase efficiently in football players with conducting a sprint intervention (Mendiguchia, Conceição, *et al.*, 2020), which. is supported by animal studies (Salzano *et al.*, 2018). Therefore, although the exact architectural set-up for increased HMI risk remains open for debate (Huygaerts, Cos, Cohen, *et al.*, 2020), reduced fascicle length remains an possible risk factor.

2.5.5.3. Motor control

Motor control is arguably the most complex area of HMI risk factors. Although in its early stages including limited evidence, research within motor control has recently gained popularity. This is likely due to advancements in sports science technology and statistical methods, increasing the accessibility and plausibility of research. Motor control can be defined as considering coordination strategies between muscles (e.g., between hamstring muscle heads and adjacent muscles such as the gluteal muscles) to complete specific movement tasks. This is also defined in literature as considering intermuscular coordination or kinetic chains (Alizadeh and Mattes, 2019). Therefore, one interesting question is whether certain motor control strategies between the hamstring muscle heads and adjacent/antagonist muscles can lead to unsustainable movement during higher risk tasks in football.

During sprinting, the hamstring muscles are highly involved in coordinating not only one, but two joints under very high force demands under brief time constraints (Zhong *et al.*, 2017). The hamstrings are not alone in this respect. As some examples, they work closely with the gluteal muscles to accelerate the hip and the gastrocnemius to decelerate eccentric open chain torques (Dorn, Schache and Pandy, 2012). Furthermore, the complexity of coordinating movement between the hip and knee is arguably further increased by having a multifaceted origin at the pelvis. The pelvis is considered the center for transferring kinetic energy within the body (Panayi, 2010). How the pelvis interacts between its adjacent joints (the hip joint of both limbs, and the spine) provides a high degree of movement freedom. In turn, this provides the opportunity for multiple motor control strategies for completing the same task. Thus, although there are likely multiple sustainable strategies for the same task, a large degree of coordination is required to efficiently transfer kinetic energy via the pelvis. This "control" is provided by a large array of muscles that surround the pelvis in all biomechanical planes. Control over this area of the body has also been termed the "lumbo-pelvic control" (Schuermans, Tiggelen, Witvrouw, Sciences, Schuermans and Sciences, 2017) and is considered to be intertwined with the term "core control" (Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017; Schuermans, Tiggelen, Witvrouw, Sciences, Schuermans, Sciences, *et al.*, 2017). Furthermore, the complexity is increased with evidence showing that kinematically identical tasks can be completed under different motor control strategies. For example, isolated hip extension can be performed with different muscle recruitment patterns both in non-symptomatic and symptomatic populations (Schuermans *et al.*, 2015; Schuermans, Tiggelen, Witvrouw, Sciences, Schuermans, Sciences, *et al.*, 2017; Sung *et al.*, 2019). In turn, two individuals can have the same strength levels but possess different muscle recruitment strategies to perform the same task. This is possible due to most joints in the body having multiple agonists, including the hamstrings themselves, which provides flexibility for compensation. This means that when one muscle is not functioning properly, other synergist muscles start contributing additional workload (Blandford, McNeill and Charvet, 2018). This has been repeatedly observed in previously injured HMI populations (Opar *et al.*, 2013; Schuermans *et al.*, 2014; Buhmann *et al.*, 2020), albeit unknown whether the neuromuscular deficiencies observed were already present before injury.

In testing motor control strategies for assessing the increased risk for an index HMI, Schuermans *et al.*, (2015) innovative approach provided initial evidence that specific motor control strategies may increase index HMI risk . The study demonstrated that during a fatiguing eccentric leg curl task, the risk was strongly related to the capacity of the ST muscle to aid the BF in the task (Schuermans *et al.*, 2015). In other words, hamstring muscle heads need to work together at an intermuscular level to share eccentric load. In another isolated movement task, the same research group demonstrated that football players were eight times more likely to sustain a HMI if during prone hip extension the hamstring muscles were activated after the lumbar erector spinae instead of the other way around (Schuermans, Tiggelen, Witvrouw, Sciences, Schuermans and Sciences, 2017). This study also provided the first prospective evidence of this important interaction between adjacent muscles. Consistent with this finding, another study the same research team showed that lower amounts of normalized EMG activity of the trunk muscles (internal and external abdominal obliques, erector spinae at the thoracic and lumbar levels) and the gluteus maximus during the airborne phase of sprinting, were associated with an increased HMI risk (Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017). The authors concluded that uninjured players potentially possessed higher motor control in the lumbo-pelvic region, reflected by the higher EMG activity in large agonists in this region (Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017). Interestingly, a study among Australian football players showed that increased gluteus medius activity during running was associated with increased HMI risk (Franettovich Smith *et al.*, 2017). However, EMG signals can be difficult to interpret in isolation and ideally kinematic analysis should also be included. On this note, Dr. Schuermans' research team demonstrated in a follow-up publication among football players that excessive APT and thoracic side bending during maximal sprinting increased the risk of an index HMI (Figure 13, A vs. B) (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017). Increased APT was also observed in Gaelic football players with previous HMI (Daly *et al.*, 2016). Furthermore, increased thoracic bending has also been shown to be associated with increased HMI risk in rugby players (Kenneally-Dabrowski *et al.*, 2019). Both of these issues have been reflected to represent a lack of lumbo-pelvic control or "core" control (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Kenneally-Dabrowski *et al.*, 2019). Exactly why lumbo-pelvic control is lost is unclear, even if multiple theories have been proposed based on the available evidence. With their origin at the ischial tuberosity, the biarticular hamstrings are highly involved in providing posterior pelvic tilt torque to resist APT (Chumanov, Heiderscheit and Thelen, 2007; Panayi, 2010). This action is aided by other muscles, such as the gluteus maximus (Chumanov, Heiderscheit and Thelen, 2007). Thus, in theory, if individual hamstring muscle heads or other muscles within the synergistic muscle chain do not adequately support posterior pelvic tilt, force produced by antagonists (such as the iliopsoas) can dominate and pull the pelvis into anterior tilt (Chumanov, Heiderscheit and Thelen, 2007). Increased APT leads to increased length and tension in the hamstrings when the lower limbs are dynamically interacting, which may likely increase the strain injury risk (Chumanov, Heiderscheit and Thelen, 2007; Panayi, 2010; Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017). Furthermore, increased tension via APT is not shared evenly between hamstring muscle heads, with SM and then BFlh increasing the most in tension (Nakamura *et al.*, 2016). BFlh has also been proposed to have more responsibility for pelvic stability as it is the only hamstring muscle with connections to the sacrotuberous ligament via the ischial tuberosity (Vleeming *et al.*, 1989). According to simulation work by Hammer *et al.*, (2019), when this ligament is cut, the pelvis motion increases by 164 %. This potentially demonstrates the larger role of the BFlh in controlling movement at the pelvis, which is proposed to be improved with adequate pull provided by BFlh (Vleeming *et al.*, 1989; Hammer *et al.*, 2019). Notably, APT can also be a motor control strategy to temporarily increase the internal moment arm of the hamstrings (Hogervorst and Vereecke, 2015). However, this likely negatively influences the moment arm in other synergist muscles, such as the gluteals (Németh and Ohlsén, 1985). Therefore, although increasing APT may be momentarily mechanically advantageous, it places the hamstrings in a "danger zone" in which there may be less room for error.

Similarly, thoracic side bending can be a compensation strategy for the pelvis lacking stability in the frontal plane (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Kenneally-Dabrowski *et al.*, 2019). This might be because when the pelvis drops towards the swing leg, bending the lower quadrant of the spine more laterally, can lead to center-of-mass moving away from the stance leg (Figure 13, C vs. D). This has to be compensated somehow to maintain balance, so the upper quadrant of the spine (thoracic) has to bend the opposite direction; medially towards the stance leg (Figure 13, C vs. D). As the sample sizes have been relatively small in the aforementioned studies, the evidence for the importance of considering motor control as a risk factor for HMI is currently limited (Green *et al.*, 2020; Wolski *et al.*, 2021). Furthermore, the practicality of accurately testing motor control in football club settings remains challenging. However, as there no evidence to refute its importance in football, exploring its integration is interesting for many stakeholders (Buckthorpe *et al.*, 2019).

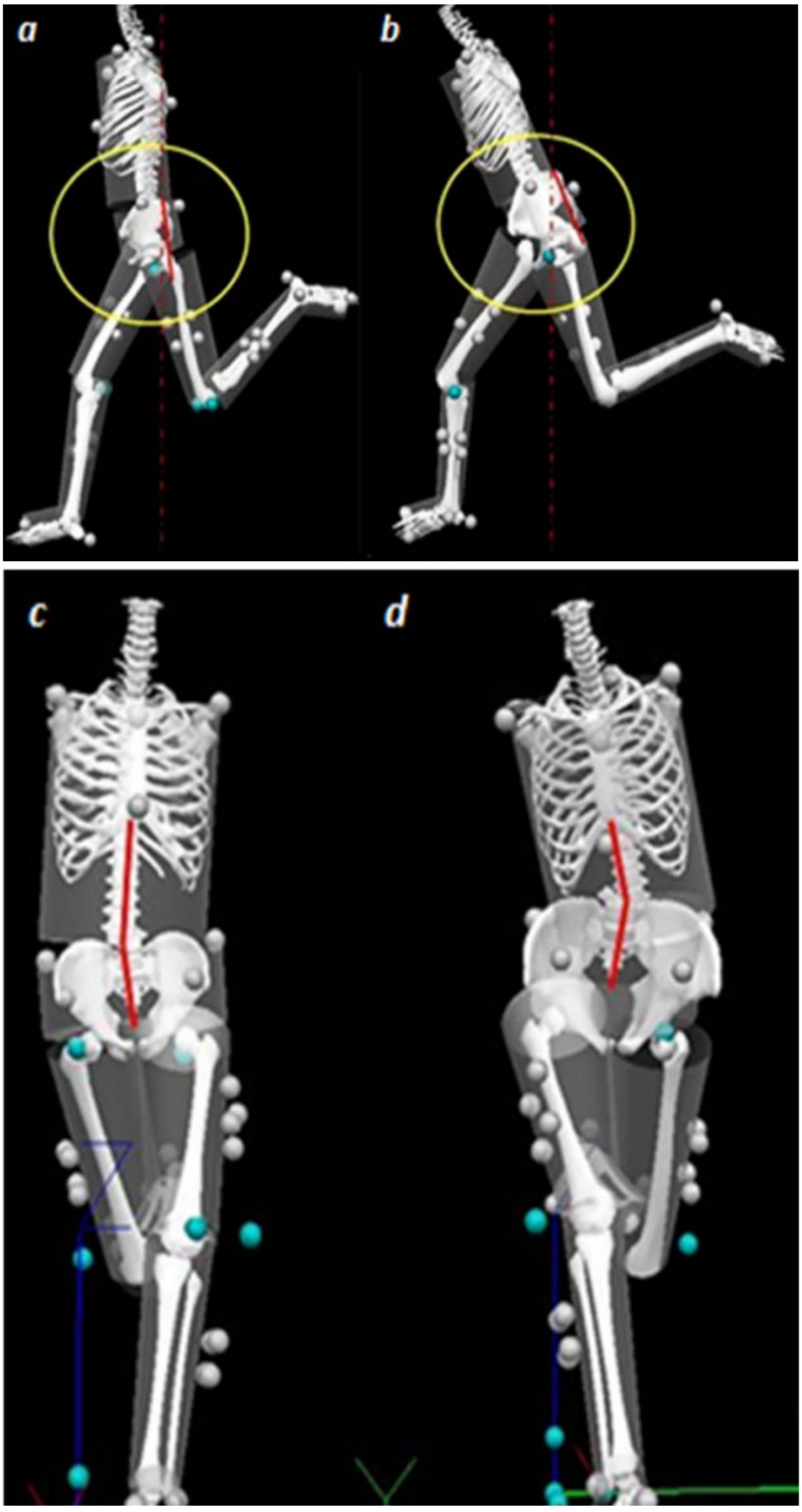

Figure 13. Sprint kinematics that may lead to hamstring injury. Sagittal plane (A, B) and frontal plane (C, D) view of non-injured athletes (A, C) vs. Injured football athletes (B, D) from Schuermans et al. (2017).

2.5.5.4. Fatigue tolerance, general conditioning, and sprint volume

Whether HMI is the result of an isolated event or an accumulation of eccentric contractions during repeated dynamic actions (causing neuromuscular fatigue), remains unclear (Baumert *et al.*, 2021). For example, fatigued animal muscle appears to absorb less energy while lengthening (Figure 14, point A) (Mair *et al.*, 1996), which may indicate relevancy for HMI.

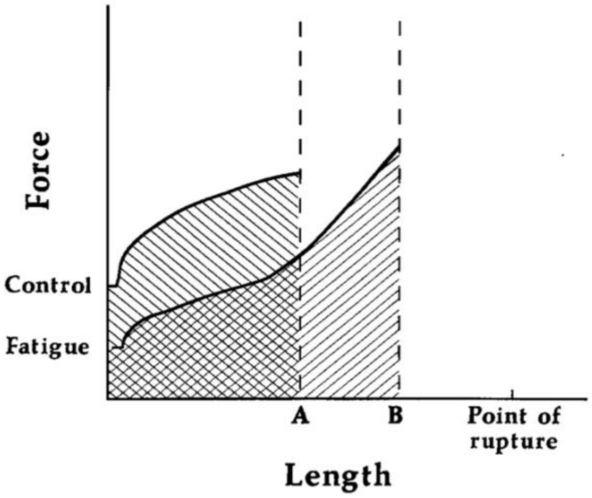

Figure 14. Muscle energy absorption capacity in non-fatigued and fatigued muscles presented by Mair et al. 1996. At point A we can see that a muscle has absorbed less energy during active lengthening if fatigue is present. Point B is the point where irreversible muscle damage begins to occur, irrespective of whether the muscle is fatigued or not. However, to absorb the same amount of energy as the non-fatigued muscle, the fatigued muscle has to lengthen further close to point B.

HMI have been shown to take place more frequently in some football populations at the end of the first half or match, and thus potentially under fatigue (Woods *et al.*, 2004). Indeed, measurements of neuromuscular fatigue following repeated sprints indicate both central and peripheral fatigue are present in the hamstring muscles (Marshall *et al.*, 2014; Baumert *et al.*, 2021). Central fatigue is related to the spinal cord or brain, whereas peripheral fatigue is related to changes at or distal to the neuromuscular junction (Wan *et al.*, 2017). Fatigue over time seems more related to peripheral components (Baumert *et al.*, 2021). Furthermore, it seems that this peripheral fatigue is more present in fast twitch fibers compared to slow twitch fibers (Baumert *et al.*, 2021). This may partly explain why a recent study found that professional football players with faster fiber typology (non-invasively estimated based on the carnosine concentration) in the soleus had a 5.3-fold higher risk of sustaining an index HMI compared to slow typology players (Lievens *et al.*, 2021).

Other hamstring muscle related biomechanical variables that have been measured pre-post repeated sprint protocols or simulated football matches include maximal isometric strength and changes in sprint kinematics. Substantial drops (16-20 %) in hamstring muscle strength have been shown after a simulated football match (Delextrat *et al.*, 2018; Matinlauri *et al.*, 2019). In terms of changes in sprint kinematics after repeated sprints, one study showed increases in APT (Small *et al.*, 2009), and two recent studies showed changes in knee extension during the terminal swing (Baumert *et al.*, 2021, Wilmes *et al.*, 2021). Increased APT can be a compensatory movement to increase the mechanical advantage of the hamstring muscles (Hogervorst and Vereecke, 2015), causing increased tension (Nakamura *et al.*, 2016). This increased tension via APT may be related to simultaneously decreasing tension via reduced knee extension as shown in previously injury HMI populations (Daly *et al.*, 2016; Higashihara *et al.*, 2019). Therefore, considering the players non-specific (intramuscular) and specific (intermuscular) fatigue tolerance may be of interest. In terms of HMI risk factors, there is only one study among football players that has assessed the influence of a fatigue related parameter. Schuermans *et al.*, (2015) showed that the risk of sustaining an HMI was increased in players with previous injury and poor strength endurance scores in a knee flexion task. The presence of lower fatigue tolerance in previously injured hamstring muscle populations has also been shown in more specific circumstances. Lord *et al.,* (2019) showed that calculating mean differences in between-limb horizontal force production during repeated sprints predicted with good accuracy players with previous HMI. This test format has not been studied among non-injured players to assess index HMI risk, but it may reflect inadequate post-injury rehabilitation. The only study that has been able to show a fatigue related index HMI risk factor was completed also among Australian football players. Players that sustained a right index HMI injury during the season completed significantly less repetitions during a single leg hamstring bridge exercise to failure (Freckleton, Cook and Pizzari, 2014).

A sudden increase in high-speed sprint volume has already been discussed as an extrinsic risk factor in sprint-based team sports. Seemingly contrarily, low exposure to high-speed sprinting is also a strong risk factor, and appropriate conditioning to high-speed sprinting on a weekly basis seems to reduce risk (Malone, Roe, Doran, Gabbett and Collins, 2017; Colby *et al.*, 2018; Malone, Owen, *et al.*, 2018). Therefore, it is possible that players are substantially fatigued from such sudden increases in volume and not conditioned appropriately. Furthermore, Malone, Owen, *et al.,* (2018) study among football players reported that higher chronic training loads and better aerobic fitness also supported lowering the risk of injury. Higher levels of aerobic fitness have been supported in other team sport cohorts (Malone, Roe, Doran, Gabbett and Collins, 2017a). However, as mentioned, it has not been tested whether this directly relates to increased HMI risk and whether specific types of fitness tests could be more predictive (such as repeated sprint tests).

2.5.5.5. Range of motion

Joint range of motion is considered to represent muscle flexibility and is the extent of movement of a joint measured in degrees (active, passive, or a combination of both) (Holt, Holt and Pelham, 1995). This represents both stretch tolerance, and the physiological stiffness (i.e., resistance to deformation) and compliance (i.e., inverse of stiffness) of the structures within the MTU. Long-term increases in range of motion have been more attributed to reductions in passive stiffness instead increases in pain tolerance (Opplert and Babault, 2018). The hamstring muscles range of motion has been moderately associated with optimal length (associated with the angle of peak torque) and the degree of MTU strain during sprinting, especially the most injured hamstring muscle the biceps femoris long head (Figure 15, A and B) (Wan *et al.*, 2017a, 2017b).

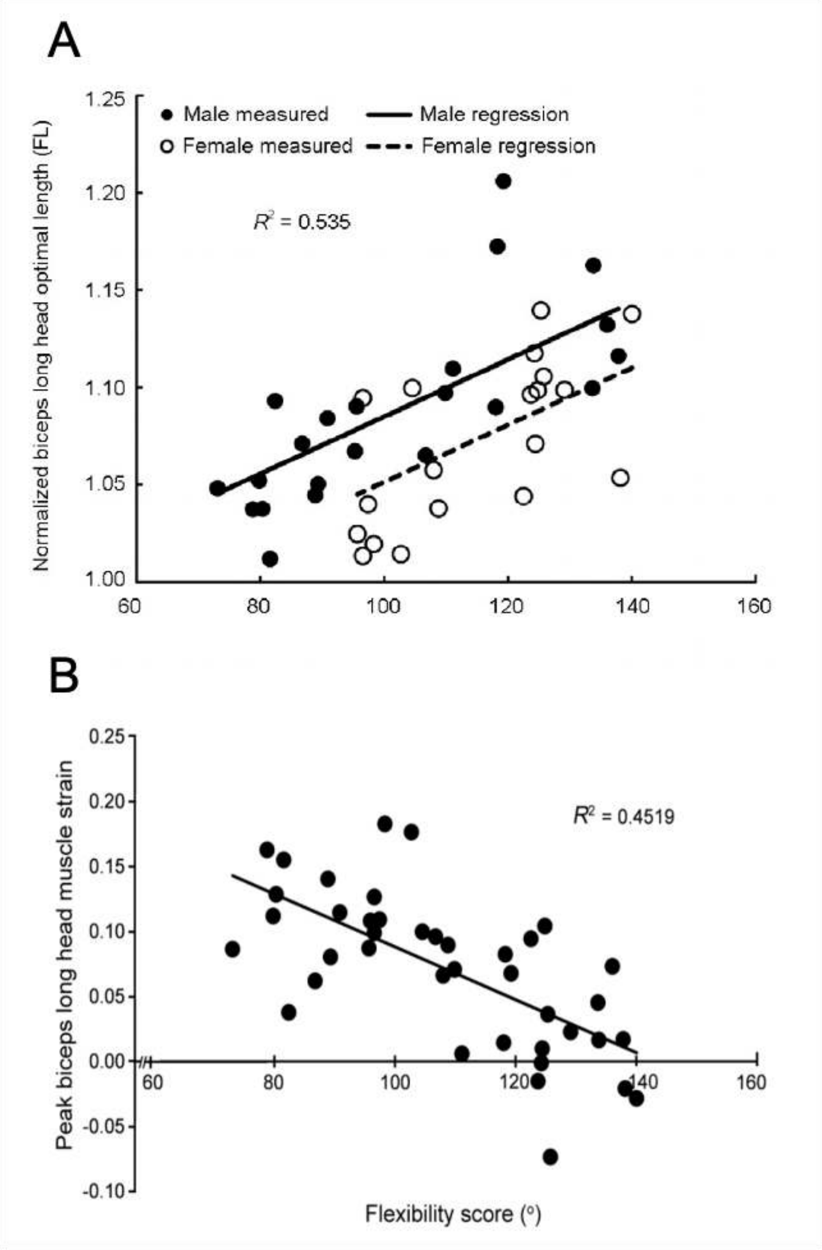

Figure 15. Relationships between flexibility score and biceps femoris long head optimal length and muscle strain during sprinting. The top figure (A) represents Wan *et al.*, (2017a) results, where they tested the relationship between passive straight leg raise (PSLR) and BFlh optimal length normalized to femur length in both genders. Optimal length was measured via slow isokinetic contractions. On the bottom (B), Wan *et al.,* (2017b) follow-up study among both sexes showed that hamstring flexibility (via the PSLR test) also explained to a moderate degree the amount of strain experienced during sprinting (hamstring length increase past optimal length). FL: Femur length.

Improvements in range of motion have also been associated with reductions in MTU stiffness (Wilson, Elliott and Wood, 1992). In theory, football players tested clinically possessing a lower range of motion may be stiffer and spend on average more time in lengths past optimal during sprint related football tasks, increasing the strain injury risk. Furthermore, as overstretch related HMI also occur in football (Ekstrand *et al.*, 2012), range of motion testing may be valuable.

Unfortunately, range of motion testing data from large cohort studies in elite level football players exhibits weak validity (van Dyk, Farooq, *et al.*, 2018). On the other hand, methods used in different cohort studies differ, using multiple different tests (different forms of both passive or active testing), making it more challenging to make strong conclusions (Bradley and Portas, 2007; Henderson, Barnes and Portas, 2010; Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017; van Doormaal *et al.*, 2017; van Dyk, Farooq, *et al.*, 2018). Of the four studies that used multivariable statistical models, three showed stronger relationships for decreased hamstring muscle range of motion contributing to increasing the risk of sustaining a HMI within football (Bradley and Portas, 2007; Henderson, Barnes and Portas, 2010; van Dyk, Farooq, *et al.*, 2018; Ayala *et al.*, 2019). Given active testing might capture different aspects of apprehension with the movement, it should probably be prioritized during testing selection (Askling, Nilsson and Thorstensson, 2010; van Dyk, Farooq, *et al.*, 2018).

2.5.5.6. Psychological and lifestyle factors

Although this thesis will focus on physical traits and their relationship with HMI risk, psychological and lifestyle factors are essential to consider in holistic training environments for all injuries. Research by Ivarsson, Johnson, and Podlog (2013) demonstrated that trait anxiety, negative-life-event stress, and daily hassle were predictors of injuries among professional Swedish football players, accounting for 24 % of the variance in injuries. In terms of HMI, there is a large deficiency in studies that aim to assess the association between the players subjective experience and injury risk. After RTP from a index HMI, one study found that reported localized discomfort from hamstring muscle palpation increased the likelihood of reinjury nearly four times compared to athletes that did not report discomfort (De Vos *et al.*, 2014). In the same study, baseline MRI findings did not increase the risk of reinjury, despite the presence of abnormalities. Thus, psychological factors could also be involved, such as catastrophizing and pain-related fears (Thibault *et al.*, 2008; Main and Watson, 2010). Ayala *et al.,* (2019) was the first HMI risk factor study to include the football players perceived sleep quality into a multivariable statistical model. They found that sleep quality was an important risk factor, as it was the most consistent variable in all the tested machine learning classifiers (Ayala *et al.*, 2019). This suggests that subjective data is likely crucial within a holistic injury management system in football.

2.5.6. FUTURE DIRECTIONS FOR MODIFIABLE INTRINSIC RISK FACTORS: CHALLENGES

Literature concerning modifiable intrinsic HMI risk factors include broad suggestions for future research focus. There seems to be a consensus among scientists and practitioners on what test categories are currently likely important to consider for professional football players within HMI risk management. These include muscle architecture, fatigue, lumbo-pelvic control (or motor control), range of motion, and strength testing (Buckthorpe *et al.*, 2019; Bisciotti *et al.*, 2020). Some authors suggest examining inter-limb asymmetries within some of these categories (Lehance *et al.*, 2008; Helme *et al.*, 2021). Within each of these categories, there exists different degrees of methodological uncertainty, and practical challenges. In many cases, implementation of gold-standard testing protocols is not plausible due to required skill-sets, budgets, test duration, and facility requirements (device mobility) among other challenges (Chimera and Warren, 2016; van Dyk, Farooq, *et al.*, 2018; Adkins and Murray, 2020; Sarto *et al.*, 2021). In terms of clinicians skill-set, some measurement devices require more competency than others. For example, hamstring architecture via extended field-of-view ultrasound or lumbo-pelvic control via a 3D kinematic assessment during dynamic tasks (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Adkins and Murray, 2020; Sarto *et al.*, 2021). Budget is similarly important, as purchasing gold standard or highly accurate devices such as extended field-of-view US, high-frequency 3D kinematic camera systems, force plates, and isokinetic devices are arguably expensive. Some of these devices require larger facilities, thus are likely not very mobile.

Testing frequency has been repeatedly reported as a limitation (Dauty, Menu and Fouasson-Chailloux, 2018; van Dyk, Farooq, *et al.*, 2018). HMI risk factor studies are structured with tests performed only once during the season (generally in pre-season), despite evidence that test performance fluctuates substantially during the season (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020). The importance of frequent testing is supported in work by Dauty *et al.*, (2016) in professional football players, which showed that isokinetic variables showed limited association with injury beyond three months. The lack of studies using multiple screening rounds is likely due to the difficulty of organizing frequent comprehensive tests. Furthermore, despite their theoretical value, certain test formats may be more difficult than others to frequently program into seasonal schedules, as they may require more time for adequate recovery. This could be the case for fatigue testing or specific contraction types, such as eccentric contractions for strength testing (Philippou *et al.*, 2004). Player and/or staff buy-in also needs to be considered, as this has shown to present challenges in practice (Bahr, Thorborg and Ekstrand, 2015; Nassis *et al.*, 2019). Thus, evidence-based or guided solutions realistically need to likely overcome time, budget, mobility, and staff-skill constraints to be implemented on a large scale.

2.5.7. FUTURE DIRECTIONS FOR MODIFIABLE INTRINSIC RISK FACTORS: SOLUTIONS - A MUSCULOSKELETAL PERSPECTIVE

When testing hamstring muscle strength, it is crucial to consider adjacent muscles like the hip extensor synergist gluteus maximus (Sugiura *et al.*, 2008; Buckthorpe *et al.*, 2019). As visualized in Figure 9, hip extension joint power can approach triple that of knee flexion during sprinting (Zhong *et al.*, 2017). Modelling studies have confirmed the large role of the gluteal muscles working together with the hamstring muscles to produce this hip extension torque during sprinting (Dorn, Schache and Pandy, 2012; Pandy *et al.*, 2021). As previously mentioned, the hamstring muscles contribute substantially to the horizontal force component of the resultant GRF vector during sprinting (Morin *et al.*, 2015). However, the same research group observed that during fatiguing sprints a decrease in horizontal force was associated with a decrease in gluteus maximus EMG activity, and not the hamstring muscles (Edouard *et al.*, 2018). It was concluded that the gluteal muscles may have a protective role to compensate for the hamstring muscles during fatiguing conditions (Edouard *et al.*, 2018). Gluteal strength has not been tested in a football population for its relevance in increased HMI risk. However, reduced hip extensor strength has been found to be a HMI risk factor among elite sprinters (Sugiura *et al.*, 2008). Furthermore, as mentioned in the motor control section, reduced EMG activity of gluteus maximus during sprinting has been identified as a risk factor in a population of football players (Schuermans, Lieven Danneels, Van Tiggelen, Palmans and Witvrouw, 2017). Based on this information, a strong case can be made for testing whether hip extension strength tests within an HMI screening protocol is important in a football setting. Both knee flexor and hip extensor strength testing have shown to be reliable with hand-held dynamometry (Thorborg *et al.*, 2010), which can be considered as isometric strength testing. This mode of testing can be considered as a practical compromise (compared to eccentric isokinetic testing) in clubs with different testing constraints. One interesting finding is that recovery from maximal eccentric strength testing may be longer than isometric strength testing (Philippou *et al.*, 2004), making isometric testing potentially slightly more appealing for frequent use. Isometric strength appears associated with increased risk of secondary HMI (De Vos *et al.*, 2014). However, currently limited and conflicting evidence exists on the relevance of isometric testing for index

HMI risk assessment in sprint-based team sports (Timmins, Bourne, *et al.*, 2016; Pizzari, Green and van Dyk, 2020). Consequently, more research on the subject is needed.

In addition, the possibility of more specific strength- or force output testing should be discussed. One reason that strength tests have shown contrasting evidence for its relevance to HMI risk may be due to the lack of specificity in the tests (i.e., limb velocity, limb positions, isolation of knee and hip vs. compound testing etc.). A pilot study by Mendiguchia *et al.,* (2014) provided retrospective evidence football players returning to play after HMI rehabilitation may demonstrate substantial deficits in theoretical maximal horizontal force output (F*0*) during maximal accelerative sprints. This study was built upon earlier findings of Brughelli *et al.*, (2010), which showed that horizontal, but not vertical force limb asymmetries during submaximal printing were present post HMI rehabilitation in Australian football players. This was an interesting finding considering hamstring muscle function has been mostly associated with directing force horizontally (Jacobs and van Ingen Schenau, 1992; Jones and Caldwell, 2003; Morin *et al.*, 2015; Pandy *et al.*, 2021). In a follow-up case report, F*0* was lower before HMI (Mendiguchia *et al.*, 2016). More recently, lower F0 was associated with increased HMI risk within the weeks following sprint measurement (HR = 2.67; 95% CI: 1.51 to 4.73) among varying levels of football players (N = 286). Although more studies are needed in professional cohorts in a multifactorial context, there is potential relevance in measuring F*0* in football. Testing F*0* in this manner may more accurately be described as assessing the force output of a system of muscles of which the hamstring muscles are essential (Mendiguchia *et al.*, 2016). Therefore, it is possible that testing F*0* during a sprint could more specifically (i.e., under similar conditions where the injury takes place), albeit indirectly, provide a view of the hamstring muscles mechanical health status. Recent studies have validated cost-efficient options to assess horizontal force in sprinting, notably sprint force-velocity profiling (Samozino *et al.*, 2016; Morin *et al.*, 2019). This highly accessible field method calculates horizontal force from instantaneous velocity data derived from a maximal acceleration sprint (Figure 16).

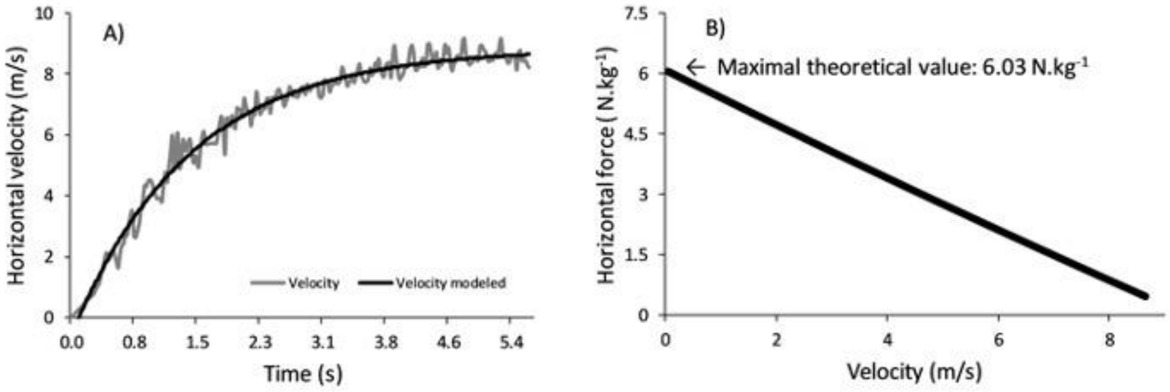

Figure 16. Calculation of theoretical maximal horizontal force from instantaneous velocity data. Figure A) shows the fitting of an exponential function over a raw velocity trace. Figure B) shows the calculation of horizontal force through the entire sprint and its extrapolation, based on the acceleration data derived from the instantaneous velocity. Figure used with permission from Lahti et al., (2021).

Importantly, instantaneous velocity data can be modelled from a variety of data sources, including typical 'split-times' (timing-gates or video-based smart phone applications) or from radar or laser devices (Morin and Samozino, 2016; Romero-Franco *et al.*, 2017). Raw velocity-time data are then fitted by an exponential function and combined with body-mass and aerodynamic friction estimates to calculate the average net horizontal GRF. Individual linear sprint force-velocity (FV) profiles are created by fitting distinct horizontal force and velocity data with a linear regression, which is then extrapolated to calculate F*0*, maximal theoretical velocity (V*0*: m/s) capabilities, and peak anterior-posterior power (Pmax: W.kg^{-1}) capabilities (Samozino *et al.*, 2016; Morin *et al.*, 2019). Here, F*0* represents the capacity to produce horizontal force at low velocities and high acceleration, which the hamstring muscles are also dominantly involved in according to new modelling study (i.e., not just maximal velocity) (Pandy *et al.*, 2021). The diverse technology upon which these variables can be extracted includes technology already common for performance testing (e.g., timing-gates, phone applications and global positioning systems), and thus increases accessibility for football clubs with different budgets. Consequently, this may provide a pragmatic option to assess acceleration performance and injury risk simultaneously.

Like strength testing, range of motion testing may represent increased value if its more specific to the injury context. This may also include testing muscles that are known to influence the hamstring muscles range of motion. Notably, the iliopsoas hip flexors have been shown to play a key role in providing force closure with the hamstring muscles in stabilizing the pelvis while showing potential in negatively influencing hamstring muscle length in sprinting (Chumanov, Heiderscheit and Thelen, 2007; Hu *et al.*, 2010). However, to our knowledge, there are no tests that quantify the simultaneous interaction of antagonistic hip flexors of the contralateral limb. Thus, creating an additional test that simultaneously measures active hamstring muscle range of motion while taking into consideration the contralateral legs hip flexors position may be warranted.

In terms of overcoming obstacles in measuring lumbo-pelvic control, less dynamic but direct measurement options of pelvic positioning, such as clinical measurements of APT, have shown potential (Bugane *et al.*, 2014; Alizadeh and Mattes, 2019; Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). Alizadeh and Mattes (2019) showed that static APT was associated with the amount of peak hip and knee flexion in the sagittal plane during the late swing phase of sprinting in a population of football players. Increased APT was associated with reductions in hip flexion but increases in knee extension during the late swing phase (Alizadeh and Mattes, 2019). As each individual hamstring muscle has different moment arms at both the hip and knee (Spoor and van Leeuwen, 1992), simultaneous length changes at the hip and knee will include different length changes among individual hamstring muscles. This may include clinically relevant changes in load distribution. Thus, as sagittal plane hip and knee movement is correlated with pelvic position (Alizadeh and Mattes, 2019), assessment of lower-limb movement in sprinting should be explored for its degree of usefulness to indirectly assess potential problems with pelvic positioning. For example, highly accessible sagittal plane filming in the aim of detecting excess rotational work being completed by the lower limbs behind the center of mass (i.e., 'a lack of "front-side" mechanics') could be valuable (Haugen *et al.*, 2018). Other time- and cost-efficient methods of lumbo-pelvic control could include validated sensors that measure dynamic pelvic movement in normal gait (Bugane *et al.*, 2014). Pelvic movement during normal gait has been shown to move with a similar wave format as sprinting (Franz *et al.*, 2009), increasing its validity. Therefore, a variety of feasible possibilities for direct and indirect assessment of lumbo-pelvic control in a professional football setting may exist.

To conclude, the aim is to design a practical battery of independent tests that consider the multifactorial nature of injuries (Chimera and Warren, 2016). Furthermore, the assumption is that the test results can be modified with training interventions, which will be discussed further in the following section. A case can be made that future HMI risk factor studies should aim to verify whether a combination of common and innovative budget friendly tests are relevant in screening protocols, in the aim of increasing access to precise multifactorial testing.

2.6. HMI RISK REDUCTION RESEARCH IN FOOTBALL

As established in the Team-sport Injury Prevention model presented by O'Brien *et al.*, (2019), after we evaluate possible risk factors, the target is to intervene. This includes implementation of different risk reduction measures, with the largest focus on modifiable intrinsic risk factors. Risk reduction strategies ideally reduce all types of HMI, therefore influencing index HMI populations and recurrent HMI populations. This is separate from rehabilitation, which may include similar strategies but different constraints.

As discussed, the strongest evidence in risk reduction strategies are RCTs, with multiple published during the past decade. The majority are in amateur football, likely owing to the difficulty in organizing RCTs in a professional or elite context. Therefore, despite being a lower level of evidence, prospective cohort intervention studies can also provide valuable data (Arnason *et al.*, 2008). Furthermore, reproducibility is essential in science to confirm causality, leading ideally to a high-quality meta-analysis (Van der Horst, Thorborg and Opar, 2020).

Askling, Karlsson, and Thorstensson (2003) performed the first HMI risk reduction intervention study with high-level footballers. Two teams from the Swedish premier league were involved (N = 30), with players randomized into either the intervention (N = 15) or control groups (N = 15). The intervention group performed eccentric overload leg curl training with the flywheel YoYo device (Figure 17). This device provides eccentric stimulus based upon the rotational energy collected into the flywheel during the concentric phase. The players were instructed to decelerate the flywheel in a smaller range of motion than the concentric phase which consequently represents a supramaximal stimuli.

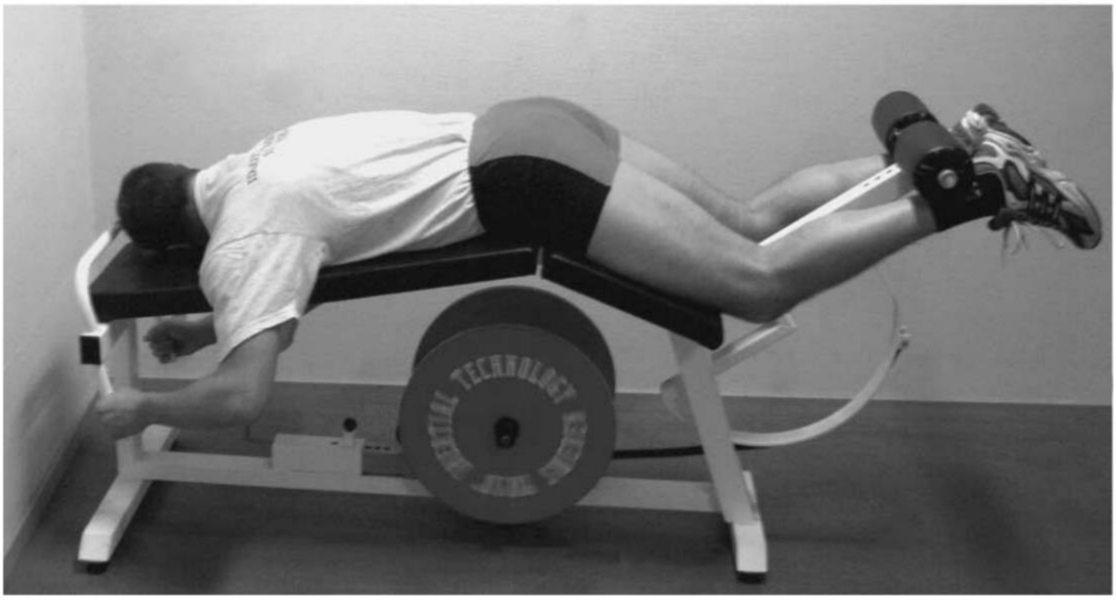

Figure 17. The YoYo flywheel leg curl exercise. This device was used in the first HMI risk reduction study among high-level football athletes (Askling, Karlsson, and Thorstensson, 2003).

This stimulus approximates the energy absorption demands the hamstring muscles experience during football, such as the terminal swing of the sprint cycle. The intervention group performed 16 sessions across 10 weeks during the pre-season, with each session including four sets of eight repetitions. Training was then discontinued during the season. The control group continued training as normal during the entire season, without eccentric focused hamstring strength training. During the season, the control group sustained significantly more injuries (index injuries: 10 vs three, for control and intervention groups, respectively; $p < 0.05$). Despite its limitations (small sample size, exceptionally high incidence of HMI in control group, and using only knee flexor-based training), this study provided initial evidence to support the importance of eccentric hamstring strength in HMI risk reduction. Thereafter, eccentric training focused interventions have attracted interest. A total of three large scale RCTs have been published within football cohorts. Two of the studies were conducted among professional or elite level players, with contradictory results. Notably, Engebretsen *et al.*, (2008) showed no additional risk reduction effect of including the Nordic hamstring eccentric exercise (NHE) among teams within the top three divisions in Norway. However, compliance was very low (21.1 %). This was also likely the main reason for the lack of results as two follow-up RCTs (one among elite and the other among amateur football players) using NHE reported around 70% reductions in HMI (Petersen *et al.*, 2011; van der Horst *et al.*, 2015). The inclusion of NHE was also supported by prospective cohort study in professional football, showing that HMI occurrence was lower in teams who used the eccentric training program compared to teams that did not use the program (RR = 0.43, $p < 0.05$) (Arnason *et al.*, 2008). The value of correcting eccentric limb asymmetries has also been researched among professional football players. Croisier *et al.,* (2008) used four levels for defining asymmetries, including eccentric and concentric between-limb asymmetries and traditional and functional H:Q ratios within-limb asymmetries. Restoring asymmetries to normal levels decreased HMI incidence (Croisier *et al.*, 2008). These studies provide strong rationale that HMI risk reduction interventions should include an intensive hamstring strength training exercise, with current evidence supporting the prioritization of eccentric training, such as the NHE (Table 4), and potentially even correcting between limb asymmetries.

Table 4. HMI interventions conducted among elite and professional football players

Intervention	Study format and population	Intervention exercise	Result
Askling, Karlsson, and Thorstensson (2003)	RCT, two teams from the Swedish premier league (N = 30).	Within-team randomization into either intervention vs. control. Intervention group used the YoYo flywheel leg curl device.	A lower number of HMI in the intervention group (3/15) vs. control (10/15) ($p < 0.05$). Compliance high (100 %).
Arnason *et al.*, 2008	Prospective cohort study, 17-30 Icelandic and Norwegian elite teams (N not reported).	Baseline injury data was collected for two seasons within Icelandic and Norwegian elite teams, whereafter teams were divided into two intervention groups. Icelandic teams performed warm-up (hamstring stretch), flexibility (partner assisted hamstring stretches), and NHE. Norwegian teams performed the same but did not include NHE.	HMI was lower teams who used NHE compared with teams that did not (RR 0.4, $p < 0.05$). Compliance moderate to low (48 %).
Croisier *et al.*, 2008	Prospective cohort study, 29 teams (n = 462).	Players with asymmetry deficits were divided into training or control groups based on the football club's decision (non-randomized). Players with between limb asymmetry in concentric (at 60 deg/s or 240 deg/s), eccentric (at 30 deg/s or 120 deg/s) and within limb asymmetry of concentric H/Q ratio (at 60 deg/s or 240 deg/s); and mixed Hecc/Qconc ratio were selected for training.	Normalizing the asymmetries reduced the risk factor for HMI to that observed in players without asymmetries (RR= 1.43; 95% confidence interval: 0.44-4.71, $p < 0.05$).
Engebretsen *et al.*, 2008	RCT, 31 teams from the top 3 divisions in Norway (N = 508).	Based on questionnaire, divided either into high risk or low risk groups. Thereafter, players were randomized within each team into intervention or control group. Intervention group performed the NHE exercise.	No influence of the intervention could be detected ($p > 0.05$). Compliance was low (21.1%).
Petersen *et al.*, 2011	RCT, 54 teams from the top 5 Danish football divisions (N = 942).	All teams stratified according to playing level before they were randomized within teams to control or intervention group. Intervention group performed the NHE exercise.	Intervention group reduced the rate of index HMI by 70% (rate ratio, 0.29; 95% CI, 0.14–0.63). Compliance high (91%). recurrent HMI were reduced by ~85 % (rate ratio, 0.156; 95% CI, 0.05–0.53).

Suarez-Arrones *et al.*, 2021	Prospective cohort study, 1 professional club (N = 24-27 per season).	Baseline data was taken from 7 seasons, whereafter two seasons were used as the intervention period. 6 components of training were emphasized (strength training, control of on-field training, physiotherapy treatment, training load management, individual training, club staff communication and individual management).	HMI reduced by 3 times during the two intervention seasons compared to the previous seasons ($p < 0.05$)

The NHE is part of the FIFA 11+ program, where it has been successful in reducing injuries in amateur football, including HMI (Thorborg *et al.*, 2017). The FIFA 11+ is traditionally viewed as a warm-up program, including basic submaximal running drills, plyometrics, and body-weight strength exercises (Van der Horst, Thorborg and Opar, 2020).

Unfortunately, limited additional intervention research exists regarding means of further improving HMI risk-reduction strategies outside of eccentric strength training among high-level football players, or even other sprint-based team sports. Croisier *et al.,* (2008) successfully reduced the HMI risk by using different strength asymmetry criteria for additional training, which included correcting concentric H:Q ratios. However, as the criteria included other contraction modes, such as eccentric asymmetry, determining to what degree restoring concentric symmetry contributed to the reduction of HMI is impossible. Since HMI risk is clearly multifactorial in nature (Buckthorpe *et al.*, 2019), and HMI continue to be the most frequent injury in professional football (Ekstrand *et al.*, 2016; Tabben *et al.*, 2021), more studies testing different types of interventions are clearly needed. A recent prospective cohort study by Suarez-Arrones *et al.*, (2021) used six different components to reduce HMI in a high level European football club across two seasons, the results from which were compared to the seven previous seasons. Thus, they aimed to approach HMI risk reduction from a multifactorial perspective. The six components were strength training, control of on-field training, physiotherapy treatment, training load management, individual training, club staff communication, and individual management. They successfully reduced HMI compared to the control seasons (2.5 vs 7.7 injuries per season, respectively; $p < 0.05$). However, as there was no control group, they provided little available information on the risk reduction approaches of the previous seasons, and reported no pre-post data in targeted training variables (Suarez-Arrones *et al.*, 2021), it is difficult to make strong conclusions on which components clearly contributed. Nevertheless, this study was an important step forward in aiming to further improve HMI risk reduction strategies. Of note, a lack of reporting of changes in targeted training variables is an issue common to most studies. Askling, Karlsson, and Thorstensson

(2003) are the only HMI risk reduction intervention among high-level football players that has reported changes in targeted training variables, in this case strength. Reporting changes in targeted variables seems even more important in studies with lower levels of evidence, such as prospective cohort studies, so that results can be interpreted with more practical takeaways. This would seem more evident for less researched but popular training categories, such as lumbo-pelvic control (Shield and Bourne, 2018). For example, Suarez-Arrones *et al.*, (2021) included lumbo-pelvic control exercises as a component of their strength training and argued for their importance, albeit in the absence of reported test data. Another prospective cohort study by Arnason *et al.*, (2008) compared range of motion (individual and partner assisted contract relax stretches) vs eccentric training (NHE). The study included two intervention groups, both of which used the range of motion exercises and the other using additionally the NHE. Only the NHE group managed to significantly reduce the rate of HMI, therefore no additional benefit was seen from the range of motion exercises (Arnason *et al.*, 2008). However, again, no pre-post training data was reported. Improvements in range of motion have been shown to reduce the amount hamstring MTU mechanical strain during sprinting by moving its optimal length to the right (Wan *et al.*, 2020). As previously mentioned, the degree of hamstring MTU strain during sprinting has been found to be correlated with the athletes range of motion test result (Wan *et al.*, 2017b). Thus, it would seem important to quantify changes in range of motion if it's a targeted variable. A recent RCT among amateur football players showed that inclusion of individualized range of motion programs reduced the incidence of lower-limb injuries (Azuma and Someya, 2020). However, they did not report separately whether HMI were reduced, but only thigh injuries as a whole. Interestingly, changes in range of motion variables were reported (including the straight leg raise), confirming that the intervention group additional training likely achieved some form of physiological change.

Other interventions within a football cohort include a RCT among amateur football players, where the researchers tested whether including bounding reduced the amount of HMI (van de Hoef *et al.*, 2018). The inclusion of bounding was rationalized as assisting in coordination and mechanical function of the hamstring muscles during sprinting. This included proposed improvements in pre-activation, eccentric strength, and stiffness (van de Hoef *et al.*, 2018). However, no evidence was found to support the addition of bounding to reduce the rates of HMI, even when accounting for compliance (van de Hoef *et al.*, 2018). Interestingly, increased stiffness was proposed as a benefit of training, when the opposite has been shown to possibly occur when using successful HMI risk reduction exercises such as the NHE (Uysal, Delioğlu and Firat, 2021). It appears more accuracy in why a certain exercise is included should be considered. While no perfect single exercise exists, strong evidence of the benefits and potential harm of each exercise are crucial.

2.7. FUTURE DIRECTIONS OF HMI RISK REDUCTION IN PROFESSIONAL FOOTBALL – A MUSCULOSKELETAL PERSPECTIVE

2.7.1. OVERVIEW

A multifactorial musculoskeletal approach is repeatedly acknowledged as ideal for injury risk reduction strategies. Nevertheless, many unanswered questions remain within professional football on what exactly should be included, and when, and how it should be performed. Furthermore, crucial practice based dilemmas need to also be considered, such as how to promote compliance among professional football players (Bahr, Thorborg and Ekstrand, 2015) and make interventions as context-specific to the demands of football as possible (Mendiguchia, Alentorn-Geli and Brughelli, 2012). There is clear evidence to support eccentric knee flexor training is clear (Van Dyk, Behan and Whiteley, 2019; Van der Horst, Thorborg and Opar, 2020), and the correction of corresponding asymmetries is supported (Croisier *et al.*, 2008; Lehance *et al.*, 2008). Furthermore, it can be argued that the inclusion of the following methods or programming details for HMI risk reduction may be of value:

i) Divide hamstring strength exercises into both hip extension and knee flexion focus, considering contraction mode, and include stimuli through a broad range of motion;
ii) Include exercises that assist in strengthening synergists, such as other parts of the posterior muscle chain (gluteals and even the triceps surae), and the hip extensor adductor magnus;
iii) Include intermuscular-coordination focused exercises to help improve control under dynamic actions, such as beginner to advanced lumbo-pelvic exercises and sprint drills;
iv) Include weekly high-velocity sprint work and consider whether sprint kinematics could be improved;
v) Consider whether training the hamstring muscles' peripheral endurance can be added, either isolated or as a part of repeated sprint protocols;
vi) Include range of motion and mobility exercises that aim to reduce passive stiffness/increase pain tolerance in the hamstring muscles, and muscles that contribute to APT, such as most of the hip flexors;
vii) Aim to reduce high volumes of strength training for muscles that may further pull the pelvis into APT (i.e., erector spinae, latissimus dorsi, hip flexors);

viii) Include elements of individualization of intervention based on a multifactorial screening;

ix) Consider what this means for the antagonists, so that the injury burden is not shifted to other parts of the body.

2.7.2. GLOBAL AND LOCAL TRAINING STIMULI

The rationale behind inclusion of stimuli (e.g., strength training, range of motion training, motor control training) for adjacent muscles and synergists (i.e., "global" stimuli) has been presented to some extent in earlier chapters. Essentially, the hamstring muscles do not work alone during dynamic tasks where injuries mostly take place such as sprinting (Dorn, Schache and Pandy, 2012). Therefore, sharing the workload makes sense for sustainable athleticism (Blandford, McNeill and Charvet, 2018). The assistance can be provided both from a dynamic perspective and stability perspective, either from an intramuscular (non-specific) or intermuscular (specific) perspective.

Providing high stimuli for the gluteus maximus, adductor magnus, and triceps surae may be interesting to provide dynamic assistance to the hamstring muscles. These muscles appear to contribute substantially to dynamic movement, by producing either hip extensor or knee flexor torque (Chumanov, Heiderscheit and Thelen, 2007; Dorn, Schache and Pandy, 2012). From an intramuscular (non-specific) perspective, providing increases in maximal strength relative to body-mass via high-quality traditional strength training exercises may be valuable. Higher relative strength in traditional compound exercises is associated with reduced lower-body injury risk in team sports (Malone, Hughes, *et al.*, 2018; Case, Knudson and Downey, 2020). Traditional strength exercises may induce positive changes in both mechanical (changes in architecture, muscle PCSA, increases in internal moment arm) and general neuromuscular properties (motor unit recruitment, firing rate) to multiple lower-limb muscles for football players (Beato *et al.*, 2020). However, since certain traditional exercises also highly stimulate antagonists, such as the quadriceps, players with different H:Q ratios should consider using different compound exercises; for example, using compound exercises that bias hip development over knee development (i.e., hip thrusts, deadlifts, wider squats) (Lahti *et al.*, 2018; Brazil *et al.*, 2021). In terms of the intermuscular (specific) perspective, training that relates to the hamstring muscles function during dynamic tasks (such as sprinting) may be interesting. Dynamic training modalities could include horizontally oriented exercises, such as basic acceleration sprints or resisted sprint training, which support the development of the horizontal force component of the GRF vector in sprint based team sports (Morin *et al.*, 2017; Cahill *et al.*, 2020; Lahti, Huuhka, *et al.*, 2020; Mendiguchia, Conceição, *et al.*, 2020).

To increase stability, similarly to dynamic training, both intramuscular and intermuscular perspectives are valuable. The force vectors of muscle fibers such as within certain areas of the gluteus maximus, internal and external obliques, and adductor magnus assist in pulling the pelvis into a posterior pelvic tilt (Chumanov, Heiderscheit and Thelen, 2007), which has the potential to contribute to decreasing tension in the hamstring muscles (Chumanov, Heiderscheit and Thelen, 2007; Kuszewski, Gnat and Saulicz, 2009; Nakamura *et al.*, 2016). Likewise, the force vectors of the hip flexors, erector spinae, and even latissimus dorsi may contribute to pulling the pelvis in the opposite direction (i.e., leading to APT) (Chumanov, Heiderscheit and Thelen, 2007; Takaki *et al.*, 2016; Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). Both groups are essential to providing a balanced pull so that a multifaceted network of force closure can be achieved. However, as established, there seems to be bias towards the pelvis rotating in certain directions, such as in the anterior direction in football players (Mendiguchia, Gonzalez De la Flor, *et al.*, 2020), which can increase HMI risk (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017). This might require intervening with exercises that aim to restore balance between agonists and antagonists. From an intramuscular perspective, isolating key muscles and reducing their passive tension caused by playing the sport may be valuable. Most notably, the iliopsoas appear large in football players when comparing to age matched cohorts (Hoshikawa *et al.*, 2012), and contribute the most to anterior pelvic pull during sprinting (Chumanov, Heiderscheit and Thelen, 2007). Furthermore, as an additional "safe guard", range of motion training (passive, active, contract-relax) has also been shown to be able to shift the optimal length of the hamstring MTU to longer lengths, leading to reduced strain during sprinting (Wan *et al.*, 2020). As range of motion exercises are considered highly non-fatiguing, they can be likely easily be integrated within a team's schedule and performed before and/or after training, even within a congested match schedule. However, range of motion exercises are not the only exercises that may influence hamstring muscle range of motion. Intermuscular exercises focused on increasing lumbo-pelvic control should also be considered. Within lumbo-pelvic control literature, the theory is that increased tension in the hamstring muscles mostly via APT can also be a compensation for the lack of control or strength asymmetries of surrounding muscles (Kuszewski, Gnat and Saulicz, 2009; Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). Interventions that focus on strengthening muscles surrounding the pelvis can reduce hamstring muscle tension (Kuszewski, Gnat and Saulicz, 2009) and dynamic pelvic tilt during normal gait (Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). Thus, using lumbo-pelvic exercises with the focus on improving intra- and intermuscular coordination of posterior pelvic tilt torque may be warranted in professional cohorts (Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). Importantly, traditional strength training exercises should vary per the level of simultaneous stimulation of muscles with APT force capacity. For example, the erector spinae has the capacity to lengthen the hamstring muscles via its APT force vector (Chumanov, Heiderscheit and Thelen, 2007; Takaki *et al.*, 2016). The erector spinae is typically highly involved in traditional bilateral compound exercises such as the squat and deadlift (Hamlyn, Behm and Young, 2007). Alternating traditional bilateral lifts with their unilateral counterpart may largely maintain the relative contribution of lower limb muscles while substantially reducing the utilization of erector spinae (Eliassen, Saeterbakken and van den Tillaar, 2018).

In terms of isolating the hamstring muscles within strength training, multiple publications have focused on demonstrating that different hamstring exercises provide different ratios of stimulus to the hamstring muscle heads (Bourne *et al.*, 2017; Hegyi, Csala, *et al.*, 2019). Generally speaking, when the knee is close to being fully extended during the most difficult part of the hamstring exercise, the BFlh and SM are utilized more, while the ST and even the BFsh role increases with knee flexion (Bourne *et al.*, 2017). A highly limited number of long-term studies exist confirming this adaptation generalization. One recent study compared the effect of 10 weeks of eccentric-concentric hip extension training vs. eccentric NHE on hamstring muscle morphology and architecture (Bourne *et al.*, 2017). Their results show that hip extension training was more effective in improving BFlh muscle volume compared to NHE, and SM volume compared to the control group (no effect was seen when comparing NHE vs. control on SM). Furthermore, there was a trend for the NHE increasing ST and BFsh muscle volume more than the hip extension exercise. However, both groups increased BFsh muscle volume compared to the control group. Both groups also equally improved fascicle length (Bourne *et al.*, 2017). Of note, hamstring muscle size has not been identified as a risk factor for HMI, so the impact of these findings is still unknown. However, a recent paper showed that a larger BFlh PCSA was moderately associated with less strength loss after repeated sprinting, whereas fascicle length was not (Baumert *et al.*, 2021). This is potentially important, as strength loss after repeated sprints was also associated with the degree of changes in the participants sprint pattern (Baumert *et al.*, 2021). This association was also shown in another recent study by Wilmes *et al.*, (2021). The potential protective benefits from increased PCSA to damage during eccentric contractions were proposed to be from improved force dispersion to the tendon (via lateral force transmission from the muscle fibers) and more muscle connective tissue of the extracellular matrix (Baumert *et al.*, 2021).

2.7.3. SPRINTING VOLUME AND KINEMATICS

In terms of increasing high-velocity sprint volume, studies have shown that if done appropriately, it seems to focus as a protective mechanism for lower-limb injuries (Malone, Roe, Doran, Gabbett and Collins, 2017; Malone, Owen, *et al.*, 2018). The fact that most HMI occur during matches, might indicate that current volumes of sprint conditioning are inadequate to cope with the game demands (Hägglund *et al.*, 2013). Furthermore, as football involves curvilinear sprinting (Bloomfield, Polman and O'Donoghue, 2007), including progressions from high-velocity linear sprinting to curved sprinting may be valuable. Recently, Fílter *et al.,* (2020) showed that performance in linear sprinting only explained 35% of performance variance in curved sprinting among football players. This demonstrates that they are likely to a large extent independent skill and, thus, should be given separate attention. However, as the players kinematics during sprinting can influence the HMI risk (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Kenneally-Dabrowski *et al.*, 2019), consideration should be given to whether technique can be addressed during sprinting via sprint drills and other constraints. Recently, Mendiguchia *et al.*, (2021) were the first to explore whether dynamic APT during maximal sprinting can be meaningfully changed with a training intervention. This was a follow-up study on a previous work of the same research team which showed reductions in dynamic APT during walking after a training intervention (Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). The moderate to large effect reduction in APT observed during different phases of the sprint cycle ($p < 0.05$) is notable but requires replication in a football cohort.

2.7.4. STRENGTH ENDURANCE

Muscle strength endurance characteristics also bear consideration as an important contributing factor to injury. The degree of hamstring muscle strength fatigue post stimulated match has been shown to be modifiable. Delextrat *et al.*, (2018) 7-week training intervention among female football players showed that hamstring muscle strength endurance training hindered eccentric strength loss post simulated match, whereas normal strength training did not. However, anecdotally including non-sport specific fatigue training may not be welcomed in many club settings. Whether more specific fatigue training such as repeated sprints have similar value should be explored (Mohr *et al.*, 2007; Iaia and Bangsbo, 2010; Kohn, Essén-Gustavsson and Myburgh, 2011).

2.7.5. INDIVIDUALIZATION OF TRAINING

Finally, individualization of these training variables should be considered. Football players within a team can substantially vary in potentially relevant HMI risk factors (Ribeiro-Alvares *et al.*, 2019), which indicates programs should likely be manipulated not only on the general demands of the sport, but per individual needs. For example, based on results of specific preliminary tests (such as screening protocols), choices are made to include specific exercises or manipulate their volume. Although difficult to complete in practical circumstances, studies have reported superiority of targeted training based on individual characteristics (Jiménez-Reyes *et al.*, 2016; Mendiguchia *et al.*, 2017). One HMI rehabilitation intervention showed substantial reductions in risk of sustaining a reinjury when using an individualized multifactorial program compared to a traditional multifactorial program (Mendiguchia *et al.*, 2017). Only one injury risk reduction study reported to individualize programs as a part of their multifactorial approach, but did not report any quantifiable criteria (Suarez-Arrones *et al.*, 2021). The psychological benefits of individualizing programs should also be considered, as buy-in to risk reduction programs is considered to be one of the most challenging obstacles to overcome in professional football (Bahr, Thorborg and Ekstrand, 2015). Individualization of programs may increase motivation of players (both intrinsically and extrinsically) due to multiple psychological reasons. One possible positive influence is the mastery of goals instead of an approach-performance goal focus, meaning that the individual is focusing on mastering something to improve sport performance instead of comparing results to the rest of the group (Kaplan and Maehr, 2007). Also, individualized programs require feedback, and frequent feedback, combined with social support can enhance intrinsic motivation (Chatzisarantis and Hagger, 2007). Individualization may also support promoting flow theory, which focuses on avoiding boredom and anxiety by providing optimal stimuli to each individual (Jackson *et al.*, 1998).

2.7. THESIS AIMS

The overarching aim of this project was to explore current gaps in the hamstring muscle risk reduction literature within football following the structure of the previously introduced TIP model (O'Brien *et al.*, 2019) (Figure 11). Specifically, after extensive evaluations (stage 1), HMI persist as the largest injury burden in professional football (Ekstrand *et al.,* 2016; Tabben *et al.*, 2021). Therefore, we must aim to further improve identification (stage 2) and intervention (stage 3) procedures.

Thus, the following specific thesis aims were developed:

I) Explore the validity of an innovative musculoskeletal hamstring screening protocol designed for professional football via testing whether the screening tests are associated with increased HMI risk;

II) Explore whether F*0* (maximal theoretical horizontal force, a variable of the screening protocol) is trainable in professional football players via conducting a resisted sprint training intervention in a professional club setting;

III) Explore if the screening protocol can be used to guide HMI risk reduction training in a professional football setting via:

   a. Introducing the framework of an innovative multifactorial and individualized HMI risk reduction program designed to further reduce HMI in professional football;
   b. Conducting a prospective cohort intervention within professional football teams to see whether HMI can be reduced from one season to another.

Each aim will be addressed within their own chapters as thesis themes and expanded with specific sub-aims where necessary. Briefly, theme I addresses the 1st aim (Chapter 3, Sections 3.1 - 3.4), theme II addresses the 2nd aim (Chapter 4, Sections 4.1 – 4.3), and theme III addresses the 3rd aim (Chapter 5, Sections 5.1 – 5.3). Chapter 6 focuses on discussing the conclusions of the thesis.

3. THEME I, HAMSTRING MUSCLE INJURY RISK EVALUATION AND IDENTIFICATION

3.1. RESPONDING TO THE FIRST RESEARCH QUESTION

It is generally agreed upon that multiple intrinsic factors should be considered for HMI risk identification (Buckthorpe *et al.*, 2019; Pizzari, Green and van Dyk, 2020). Thus, screening protocols involving multiple musculoskeletal tests are warranted. However, constraints within real-world club settings need to be considered when setting expectations in changing current protocols (van der Horst *et al.*, 2021). In terms of evaluation, professional football clubs are highly heterogenous in what type of testing facilities fit within their budget. This means that improving accessibility to efficacious testing data is of high importance. Furthermore, innovation within tests themselves is crucial, as there are still no modifiable intrinsic risk factors that have been systematically reproduced, despite controlling for confounding factors (Green *et al.*, 2020; Pizzari, Green and van Dyk, 2020). Another constraint within real-world club settings is time, which can be considered a homogenous constraint. Testing time may be limited during the season, and congested match schedules have shown to cause substantial fluctuations in performance and thus potentially test scores (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020). Typically, hamstring screening studies have involved only one pre-season testing round to screen for players at risk for the rest of the season (Green *et al.*, 2020). Thus, tests that can be repeated with relative ease should be sought after and prioritized. Furthermore, creating prevention tests that simultaneously screen for performance outcomes may improve motivation for testing (Møller *et al.*, 2021). Taken together, this created the first research questions for the thesis:

1) *Can a hamstring screening protocol be created that is potentially feasible in a range of professional football settings?*
2) *Are the test scores within the protocol associated with increased risk of hamstring injury?*

This in turn created the first aim of the thesis mentioned in the aims section:

1) To explore the validity of an innovative musculoskeletal hamstring screening protocol designed for professional football via studying whether the individual tests outcomes are associated with increased risk of hamstring injury.

The decisions for test inclusion were based on the most recent literature, possible constraints within real-world settings, and anecdotal evidence from experienced practitioners, which is presented in Figure 18. Specifically, the initial screening test categories of interest were fatigue tolerance (local, global), limb asymmetry, lumbo-pelvic control, motor patterning, muscle architecture, range of motion, and strength (local, global) (Mendiguchia, Alentorn-Geli and Brughelli, 2012; Buckthorpe *et al.*, 2019; Green *et al.*, 2020). However, when practical constraints were considered, some of these test categories were not considered to be plausible in variety of football club settings. One of our targets of the screening protocol was that it would realistically allow for frequent testing. Thus, highly fatiguing, or time-consuming tests were not considered plausible to be accepted during the season. Being able to conduct the tests in a variety of settings would also support frequent testing, thus mobility of tests was considered important (e.g., using manual dynamometry). Furthermore, budget, staff skill, and facility constraints were important to consider. For example, accurate testing of muscle architecture requires expensive equipment and a skillful clinician for reproducible results. Similarly, isokinetic testing and 3D motion analysis would likely require large facilities. Finally, tests that could be used simultaneously to assess important performance metrics were considered of value.

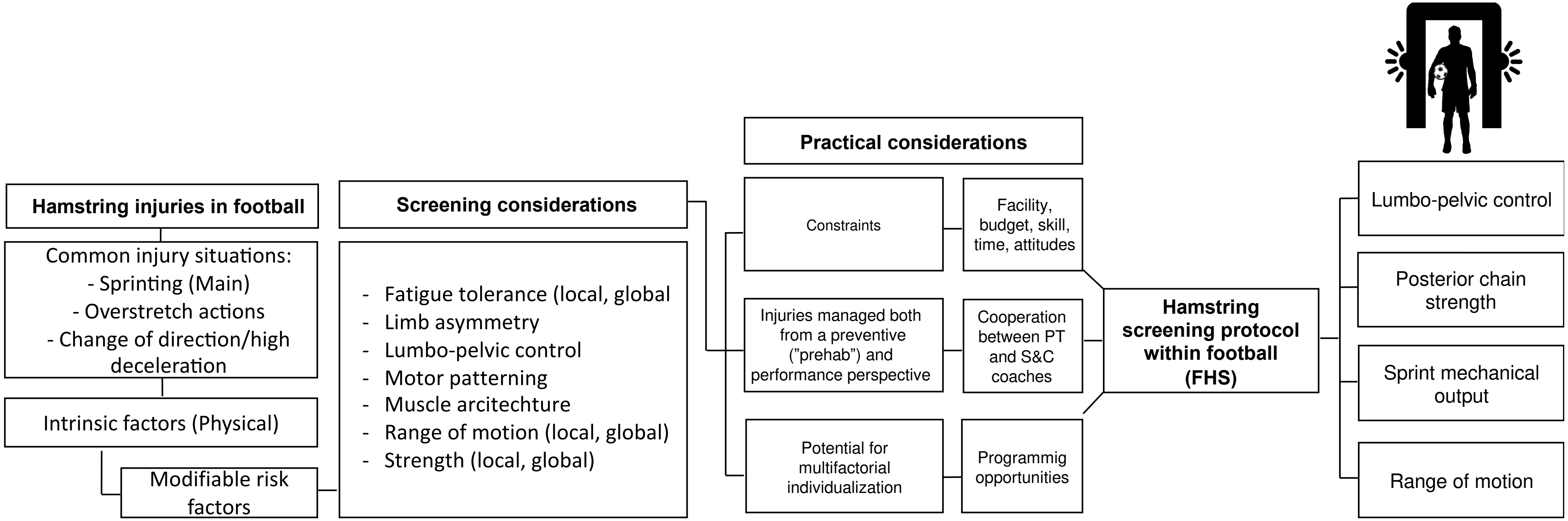

Figure 18. The logic behind the musculoskeletal hamstring screening protocol structure. Figure 18 is used and adapted with permission from Lahti et al., (2021).

Table 5 represents the musculoskeletal hamstring screening protocols tests, aims, and measurement method. The tests were divided into clinical and field tests (a total of 11 tests). The clinical tests included all but the Kick-back test and the maximal theoretical horizontal force test, which were considered field tests. Clinical tests lasted 20 minutes, including no warm-up. The clinical tests were conducted in the following order; range of motion, posterior chain strength, and the walk-test from the lumbo-pelvic control category. Field testing lasted 20 minutes, including a 10-minute warm-up. The warm-up included jogging for 5 minutes, dynamic stretching for two minutes, and sprint drills for three minutes. Timing of testing was also important, as football matches induce substantial fatigue on force production and rate of force development (Ispirlidis et al., 2008; Matinlauri et al., 2019). Maximal force seems to recover within 72 hours (Matinlauri et al., 2019). However, sprint speed may take up to 96 h (Ispirlidis et al., 2008). Thus, clinical tests were targeted to be performed a minimum of 72 hours post-match and sprint testing 96 h post-match.

Hamstring screening protocol Within football (FHS)

Clinical tests:
- 72 h from sternous activity
- Adhered order in study: Range of motion, Posterior chain strength, and the Walk test for lumbo-pelvic control.

Field tests:
- 96 h from sternous activity
- Sprint mechanical output and the kick-back test for lumbo-pelvic control.

Time window:
- 30 minutes per player (clinical tests 20 min, field tests 10 min post warm-up)

Proposed equipment:
- Manual dynamometer
- 240 fps slow-mo camera/device measuring speed of objects*
- Digital ROM assessment**
- Physio traction belt

Screening category	Aim	Test	Measurement
Posterior chain strength	High force testing of knee flexors and hip extensors and asymmetry between limbs	Knee flexor strength	Prone ISO knee flexion force (N). Hip: 0 °, knee: 30 °
		Knee flexor strength limb asymmetry	
		Hip extensor strength	Prone ISO hip extension force (N). Hip: 0 °, knee: 90 °
		Hip extensor strength limb asymmetry	
Sprint mechanical output	More specific high force testing for the hamstrings	Maximal theoretical horizontal force during sprinting	Maximal horizontal force ($N.kg^{-1}$) derived from players sprint force-velocity-profile during a 35 - maximal sprint
Lumbo-pelvic control	Dynamic pelvic movement in normal gait	Walk test	10-meter walk with a digital gyroscope placed on the S1/L5 junction
	Hip/thigh interaction in sprinting (“Kick – back” mechanism)	Kick-back test	Touchdown contralateral thigh ° + toe-off ipsilateral thigh ° in upright sprinting
Range of motion	Active hamstring and opposite hip flexor range of motion interaction and asymmetery	Jurdan test	Supine active knee extension angle (thigh at and ankle at 90 °) + opposite hip flexor angle.
		Jurdan test limb interaction asymmetry	
	Active hamstring range of motion and limb asymmetry	Active straight leg raise	Supine active straight leg thigh angle, knee extended and ankle at 90 °
		Active straight leg raise limb asymmetry	

Table 5. The sequence and details of the tests within the musculoskeletal hamstring screening protocol. ISO: Isometric contraction, N: Newton, ROM: Range of motion. Table 5 is used with permission from Lahti et al., (2021).

Figures 19-23 show images of the tests. Two out of 11 tests were innovative in nature, meaning that they have not been researched in any context before (The Jurdan test and the Kick-back test). The screening protocols reliability was piloted on a test-retest intrarater level for the clinician performing the tests in the thesis (Johan Lahti) (Lahti *et al.*, 2021). In all 11-tests, inter-day intraclass correlation coefficients (ICC ^{3,2}) ranged from moderate-to-excellent (0.72 – 0.99). Relative reliability (minimal detectable change) ranged between 6.63 – 21.5 % (Lahti *et al.*, 2021)

3.1.1. POSTERIOR CHAIN STRENGTH TESTING

Posterior chain testing aimed to test the hamstring muscles and gluteus maximus muscles load tolerance and asymmetry between limbs. The hip extensors were also tested as they have been proposed to be one of the most important adjacent synergists for the hamstring muscles (Edouard *et al.*, 2018; Buckthorpe *et al.*, 2019). For both limbs, isometric knee flexion was used to test the hamstring muscles and isometric hip extension for the gluteus maximus (Figure 19). Specifically, hip extension force was tested in a prone position with the knee bent at ~100° (depending on the calf muscles size). The dynamometer was placed on the distal femur 5 cm proximal to the knee joint line. Knee flexion force was tested with a lower knee flexion angle of 30° (i.e., compared to a normally used 90° knee position), as it may slightly bias the most commonly injured hamstring muscle the BFlh compared to the ST (Bourne *et al.*, 2017). The dynamomter was placed on the back of the heel. In both tests the players were prepared for the maximal effort by completing a short warm-up consisting of a 70 %, 80 %, and a 90% intensity contraction. The, three maximal voluntary isometric contractions were completed per leg, with the two best performances averaged. A 1-min break was used for each leg. Both tests showed good reliability (Thorborg *et al.*, 2009; van der Made *et al.*, 2019).

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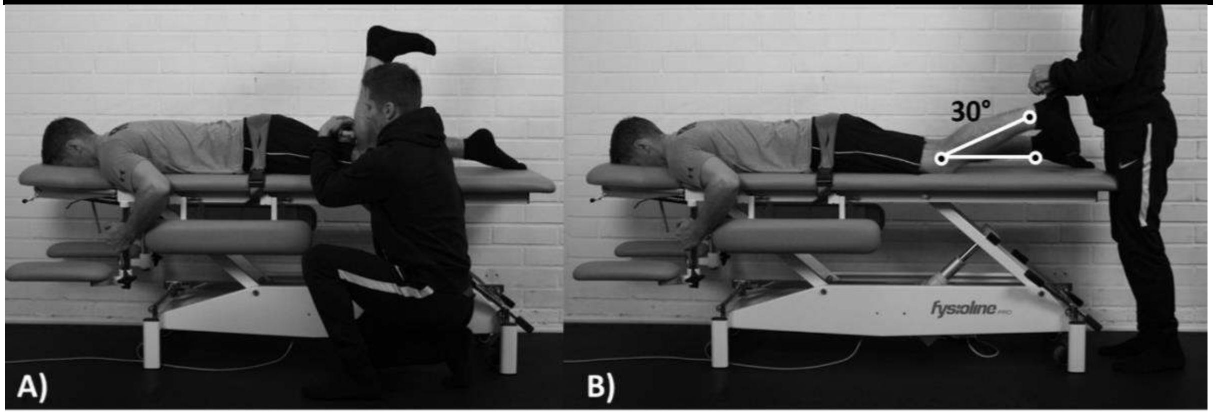

Figure 19. Posterior strength testing with manual dynaomometry. A) The hip extension strength test. B) The knee flexion strength test. Figure 19 is used with permission from Lahti *et al.*, (2021).

3.1.2. SPRINT MECHANICAL OUTPUT TESTING

The sprint mechanical output test focuses on testing the players maximal horizontal force capacity. As the hamstring muscles have been shown to be one of the main protagonists for producing horizontal force during a sprint (Morin *et al.*, 2015; Pandy *et al.*, 2021), isolating this mechanical variable may give indirect insight of the hamstring muscles health status when it is working with a chain of muscles during sprint acceleration (Mendiguchia *et al.*, 2014; Mendiguchia *et al.*, 2016; Edouard, Lahti, *et al.*, 2021). Two maximal 30-m sprints were performed with 3-min rest between sprints. Sprint FV-profiles were analysed using a validated field method (Samozino *et al.*, 2016; Morin *et al.*, 2019). As illustrated earlier in Figure 16, raw velocity-time data was derived from the radar gun (Stalker ATS Pro II, Applied Concepts, TX, USA) (Figure 20), which represents the center-of-masses motion. The raw data was fitted with an exponential function. From here, the rate of acceleration was calculated from instantaneous velocity data, which was combined with body-mass and aerodynamic friction to compute the net horizontal antero-posterior ground reaction force. Individual linear sprint force–velocity profiles are then extrapolated to calculate F*0*.

Figure 20. Field-based sprint Force-Velocity (FV) testing using a radar gun.

3.1.3. LUMBO-PELVIC CONTROL TESTING

Two tests were used to assess lumbo-pelvic control. The first test was named the "walk test" (Figure 21). The walk test aims to gain insight about the lack of control in the lumbo-pelvic region by measuring dynamic pelvic motion, which when excessive, has been associated with increased HMI risk (Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017). The Walk test was conducted by the player walking 10-m forward and back with a validated digital gyroscope placed on the S1/L5 junction (LetSense Group, Castel Maggiore, Italy) (Bugane *et al.*, 2014). The sensor samples dynamic pelvic motion at 100 Hz. From this data the peak angle ranges of the sagittal and frontal biomechanical planes are used as a test result. The test was performed twice and thereafter averaged.

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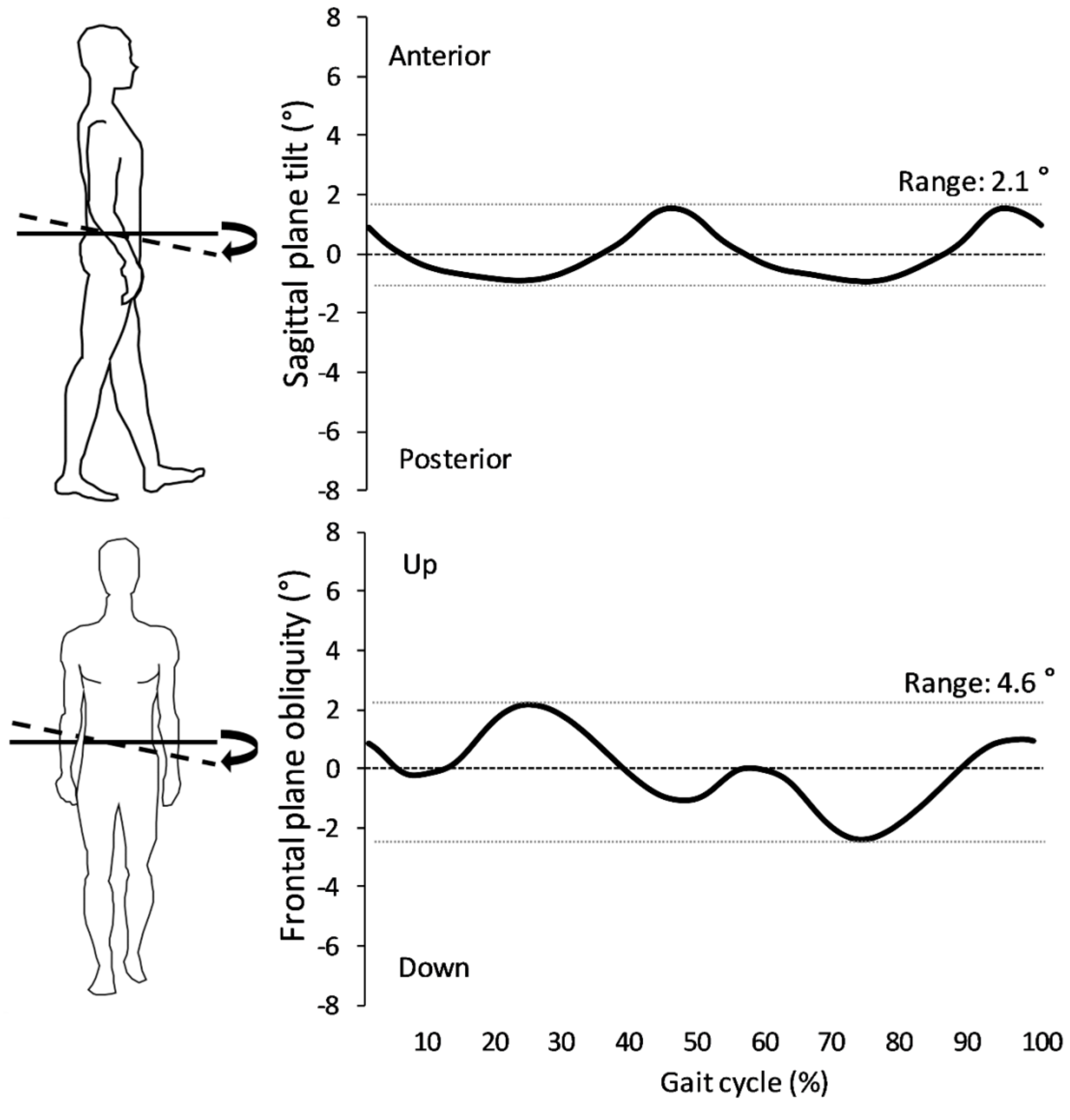

Figure 21. Lumbo-pelvic control testing via a pelvic sensor during normal gait. Figure 21 is used with permission from Lahti *et al.*, (2021).

The second test was a novel tests and was named the kick-back test (Figure 22). It aims to indirectly measure the degree of dynamic APT during sprinting. Thus, a lower degree of the kick-back mechanism was theorized to place less mechanical demands on the hamstring muscles. As a majority of HMI likely occur during active lengthening in the late swing phase (Kenneally-Dabrowski *et al.*, 2019), controlling body-segments that influence hamstring length may be of interest (Chumanov, Heiderscheit and Thelen, 2007). Chumanov, Heiderscheit and Thelen (2007) results showed that hamstring length can be substantially influenced by their antagonists on the contralateral limb via the pelvis. Thus, a reduced angle of the ipsilateral thigh during the toe-off and the contralateral thigh during touchdown was theorized to represent a running posture that may increase the likelihood of the pelvis rotating anteriorly (see Figure 22 for clear descirption). This can be considered to possibly take place due to an excessive pull from a stretched hip flexor (Chumanov, Heiderscheit and Thelen, 2007; Mendiguchia *et al.*, 2021), or due to the player ”running” out of hip-extension reserve, thus potentially compansating via hyperlordosis of the spine (Hovorka and Cawley, 2020). Consequently, during the late swing phase (where most injuries take place), this may represent a scenario where the trailing limb contributes to increasing the length of the hamstrings via the pelvis. The kick-back composite angle was averaged based on two strides from two sprints, thus four strides in total.

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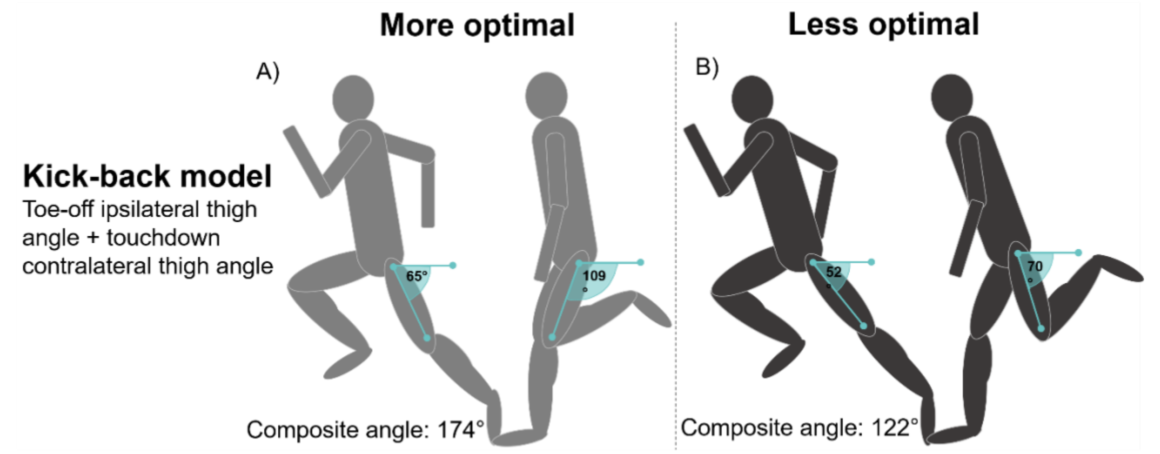

Figure 22. The kick-back test for lumbo-pelvic control. A video link for the test can be found in Appendix 1, Table 2. The composite score defines whether the player has more (A) or less (B) optimal running kinematics. A similar sprint posture can be seen from the injured football player in Schuermans, Van Tiggelen, *et al.*, (2017) prospective HMI risk association study (Figure 4). Figure 22 is used with permission from Lahti *et al.*, (2021).

3.1.4. RANGE OF MOTION TESTING

Two tests were used to gain insight of the hamstrings active extensibility with different approaches (Figure 23). Specifically, the two tests aimed to cover a larger area of lengthening related HMI, including sprint and over-stretching actions (e.g., high touches, slide-tackling). The novel Jurdan test (Figure 24, A & B) is porposed to be of interest as the iliopsoas has shown to influence the most hamstring length during sprinting (Chumanov, Heiderscheit and Thelen, 2007). Thus, quantifying the interaction between the hamstring and the opposite thighs hip flexor was of interest. The Jurdan test can be considered a combination of the reliable active knee extension test (Neto *et al.*, 2015) and the modified thomas test (Vigotsky *et al.*, 2016). Initially, the player layed supine after sitting on the edge of the table. Then, one leg was passively kept over the table while the opposite performs an active knee extension. The start start position (Figure 23, A) was where the player was told to hold their lumbar spine in contact with the table. The lumbar position was verified kinaesthetically by the clinician in the starting position. Then, the player was asked to maintain the thigh at 90° while performing the active knee extension (verified visually) (Figure 23, B). The final result was calculated based on the difference between the tibias angle of the actively lengthened leg and the opposite legs passive thigh angle. Angles are measured relative to the horizontal plane. The following example is presented in Figure 24: 65° - (−18°) = 83°, where 65° was the shin angle and −18° was the opposite leg's negative thigh angle. Another example result that leads to the same value, but different range of motion values would be 86°– (3°) = 83°. Therefore, the result does not focus on which specific leg's extensibility was the most problematic but instead focuses on the leg interaction. The ASLR test is common to literature and is considered a reliable measure (Neto *et al.*, 2015). In its extended knee position, the ASLR tests relationship to HMI was proposed to be more related to over-stretching actions compared to lenthenging that takes place during sprinting. In a prone position, the player was asked to complete maximal active hip flexion with a straight leg using a 3-s pace (Figure 23, C & D). The player was told to hold the ankle at a neutral position (90 °) and the opposite leg stuck to the table. Both tests are measured twice and averaged using a validated digital goniometer app (Goniometer Records, Indian Orthopedic Research Group) (Wellmon *et al.*, 2016). Limb asymmetry was also calculated.

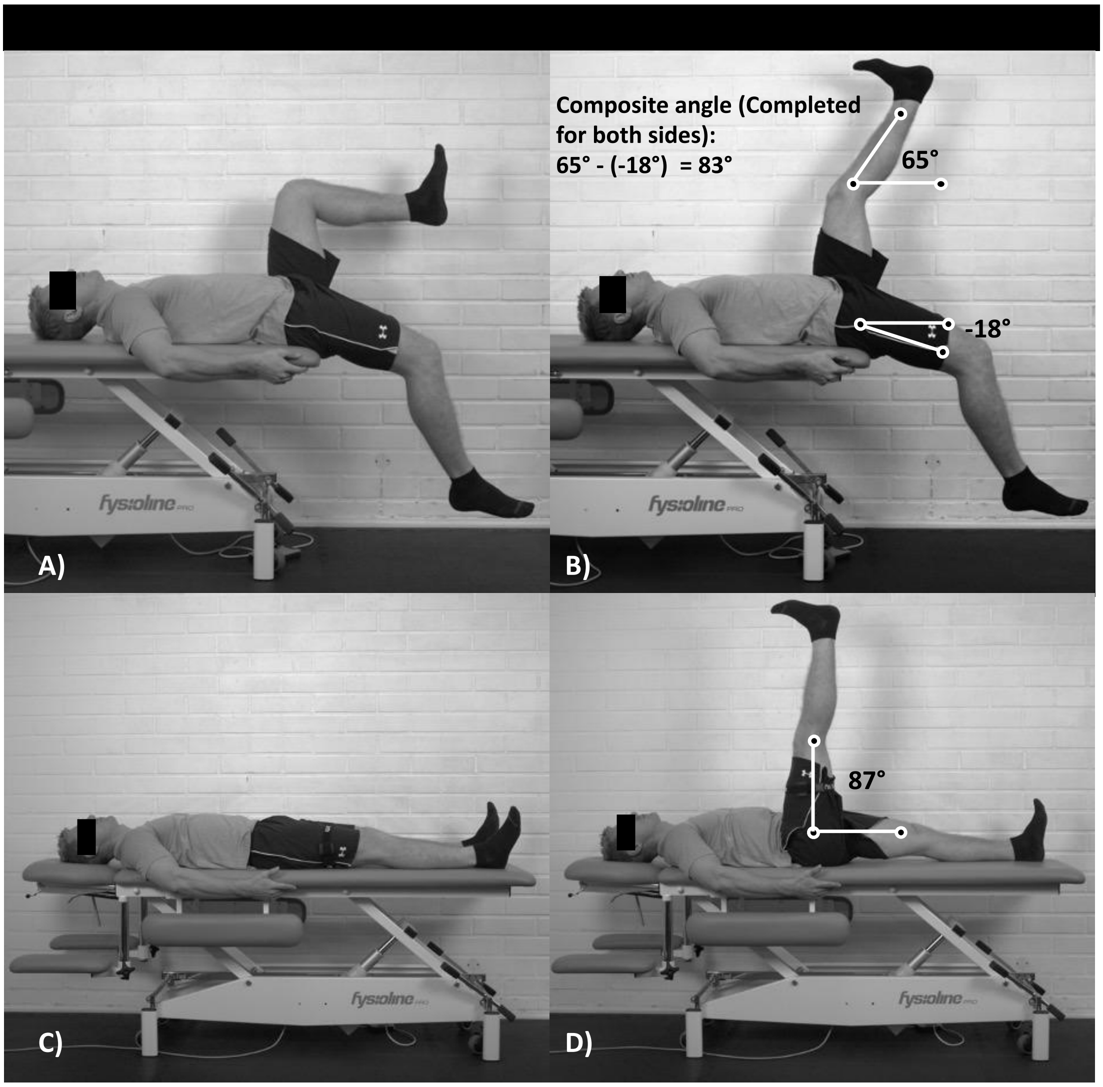

Figure 23. Range of motion testing using the the novel Jurdan test (A, B), and the traditional ASLR test (C, D). A video link for the Jurdan test can be found in Appendix 1, Table 2. Figure 23 is used with permission from Lahti *et al.*, (2021).

Next, the musculoskeletal screening protocol was implemented in a real-life setting to explore its capability to detect professional football players at higher risk of HMI. In turn, this created study I. Therefore, study I was conducted as a prospective non-experimental study similar to previous literature (Henderson, Barnes and Portas, 2010; Fousekis *et al.*, 2011; Van Dyk *et al.*, 2017; Lee *et al.*, 2018). Specifically, the screening protocol was conducted within different professional football club settings and thereafter injury data was prospectively collected.

As the first part of the TIP model is evaluation (i.e., asking "what is the current injury situation"?), it was important to confirm that the chosen cohort was in fact suffering from a similar HMI burden compared to previous literature. A matched epidemiological situation among the chosen cohort compared to previous literature would likely increase the efficacy of the results.

Finally, our target was to prove improved feasibility by conducting the screening protocol at least twice during the season. It was thought that if the screening protocol was any longer or strenuous, it would be unrealistic to expect cooperation from the recruited teams, especially for more than one testing round. This also allowed to test whether screening test scores changed during the season compared to previous literature (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020).

3.2. STUDY I: A NOVEL MULTIFACTORIAL HAMSTRING SCREENING PROTOCOL: ASSOCIATION WITH HAMSTRING MUSCLE INJURIES IN PROFESSIONAL FOOTBALL (SOCCER) – A PROSPECTIVE COHORT STUDY.

Accepted into Biology of sport (5.12.2021)

Head title:

A NOVEL MULTIFACTORIAL HAMSTRING SCREENING PROTOCOL

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ABSTRACT

The aim of this pilot study was to analyze the potential association of a novel multifactorial hamstring screening protocol with the occurrence of hamstring muscle injuries (HMI) in professional football. 161 professional male football players participated in this study (age: 24.6 ± 5.36 years; body-height: 180 ± 7.07 cm; body-mass: 77.2 ± 7.70 kg). During the pre- and mid-season, players performed a screening protocol consisting of 11 tests aimed to evaluate their performance in regards to four main musculoskeletal categories: posterior chain strength, sprint mechanical output, lumbopelvic control and range of motion. Univariate cox regression analysis showed no significant association between the isolated test results and new HMI occurrence during the season (n=17) ($p>0.05$). When including injuries that took place between the pre- and mid-season screenings (~90 days), maximal theoretical horizontal force ($F0$) was significantly associated with higher HMI risk between pre- and mid-season evaluations (n=14, hazard ratio; 4.02 (CI95% 1.08 to 15.0, $p=0.04$). This study identified that 1) no single screening test was sufficient to identify players at risk of HMI within the entire season, while 2) low F0 was associated with increased risk of HMI when occurring closer to the moment of screening. The present results support the potential relevance of additionally including frequent F0 testing for HMI risk reduction management. Replication studies are needed in larger cohorts for more accurate interpretations on univariate and multivariate levels. Finally, future studies should explore whether improving F0 is relevant within a multifactorial HMI risk reduction approach.

Keywords: soccer, injury prevention, sprinting, risk factors.

INTRODUCTION

Hamstring muscle injury (HMI) occurrence represents one of the largest injury dilemmas in professional football, ranging between 12-15% of all football-related injuries [1,2]. This has been shown to compromise team success, caused by both the amount of absence time of the injured players as well as a tendency towards declined performance capacity when returning to sport [3,4]. Large efforts have been made within prospective research to evaluate and improve awareness of associated intrinsic risk factors [5]. These efforts aim to improve the accuracy of injury risk reduction interventions and player load management [6]. It is generally agreed that HMI risk in football depends on multiple potentially modifiable risk factors [5,7]. Therefore, hamstring screening protocols should also be multifactorial to better meet the multifactorial nature of the injury and to improve the individualization of interventions.

Musculoskeletal screening protocols (and their included mode of analysis) that accurately predict players at risk for HMI are still in their infancy [6,8]. This means that it is difficult for contemporary clinicians to make accurate risk management judgement calls based on screening results [6]. Therefore, screening protocols that simultaneously test for performance and HMI risk outcomes may be considered more useful for contemporary clinicians [9]. In this manner, the risk of wasting the time of players with false positive results is reduced. Furthermore, screening protocols should be time- and cost-efficient, as this increases the probability of frequent and widely spread use. More frequent testing may also be essential to the screening information quality, as studies have shown screening results can fluctuate substantially during the season [10,11]. Thus, organizing additional screening opportunities after the preseason may, in turn, better reflect the current status of the player at the time of injury during the season [5,12,13].

Recently, a novel musculoskeletal hamstring screening protocol for football (Football Hamstring Screening: FHS) was introduced [9]. This multifactorial protocol aims to provide clinicians with a cost- and time-efficient alternative for HMI risk management from both a risk reduction and performance perspective [9]. Specifically, the protocol's 11 tests last ~30 minutes per player, with the total test device budget of ~3000 USD. Furthermore, the intra-rater study has shown initial promise for the protocol to be reliable within a football cohort [14]. Based on previous literature and anecdotes from experienced practitioners, the FHS has been divided into four screening categories that are considered important in football, including a total of 11 tests. The respective four categories are (1) posterior chain strength, (2) lumbopelvic control, (3) range of motion, and (4) sprint mechanical output [9]. There is now a need to explore the efficacy of the newly introduced hamstring screening protocol for football to identify players at risk for HMI.

Therefore, the primary aim of this pilot study was to analyze the potential association of each of the four components of this screening protocol, evaluated by means of 11 separate tests, with the occurrence of HMI. The second aim was to determine whether screening results change during the season.

METHODS

Study design and overall procedure

We conducted a single-season prospective cohort pilot study among Finnish professional football players. Screening tests were conducted within this cohort during the end of pre-season (March 2019) and the mid-season (June 2019) periods. Prospective data collection as regards sport exposure and injury occurrence were collected throughout the entire season, from April to October 2019. The study was approved by the Saint-Etienne University Hospital Ethics Committee (Request number: IORG0007394; Record number IRBN322016/CHUSTE).

Population

We recruited 161 football players from nine teams using convenience sampling (age: 24.6 ± 5.36 years; body-height: 180 ± 7.07 cm; body-mass: 77.2 ± 7.70 kg), with one recruited from the primary league in France (Ligue 1), and eight from the premier Finnish football division (Veikkausliiga). The objectives, procedures, and risks of the study were explained to the coaching staff and players through verbal discussions, documentation, and oral presentations. Inclusion criteria included completing all screening tests during the preseason measurements, playing the entire in-season in the same team, and injury and exposure data being collected according to the study guidelines. Exclusion criteria included having ongoing rehabilitation and being a goalkeeper, since the respective playing position carries a low HMI risk [15]. All participating players provided written informed consent prior to study participation.

Data collection

All included football players completed 11 tests included in a hamstring screening protocol during the pre- and mid-season. We performed two screening tests sessions to try to account for seasonal fluctuations in physical scores [10,11]. All tests were conducted in each team's training environment (clinic and on-field). The FHS is presented in the Table 1, with details of its four components and 11 screening tests, as well as the intrinsic risk factors, the musculoskeletal elements, the assessed variables, and the corresponding experimental equipment used in testing. All measurements were carried out in each teams testing quarters by the same experienced practitioner (JL). At the start of the season (i.e., during the pre-season testing), previous HMI within the last two seasons, playing position, age, and basic anthropometrical information (height, body-mass), were recorded for all players through questionnaires. Body-mass data were updated during the mid-season testing. Injury history was confirmed by the team physiotherapist and anthropometric information was measured during the first day of screening testing.

Table 1. Football Hamstring Screening protocol with its four component and including the 11 screening tests and their respective methods and equipment used (Total tests: 11, including asymmetry)

Component of the screening protocol	**Anatomical elements/property**	**Assessed variable**	**Experimental equipment**
Lumbo-pelvic control	Pelvic movement in normal gait	Peak pelvic anterior/posterior tilt and obliquity during walking (10-m)	Gyroscope sensor [21]
	Sprint technique(“Kick-back mechanism”)*	Thigh angle during touchdown and toe-off in maximal upright sprinting*	Slow motion camera [14]
Posterior chain strength (+ asymmetry)	Hip extensor isolative strength	Isometric force at 0° of hip ext. and 95-100° of knee flexion ($N.kg^{-1}$)	Hand-held dynamometer Microfet II [24]
	Knee flexors isolative strength	Isometric force at 0° of hip ext. and 25-30° of knee flexion ($N.kg^{-1}$)	
Range of motion (+ asymmetry)	Hamstrings extensibility	Thigh angle during active straight leg raise (ASLR)	Goniometer records app [19]
	Hamstrings in combination with hip flexors	Active knee extension with opposite thigh passive angle (Jurdan test)	
Sprint mechanical output	Dynamic posterior chain strength during maximal sprint acceleration	Maximal horizontal force (F*0*) during 2 x 30-m sprints ($N.kg^{-1}$)	Stalker ATS II radar [26]

* Sprint technique testing (Lumbopelvic control) was tested at the same time as sprint mechanical output testing

The FHS consists of 11 screening tests within the following four categories; posterior chain strength, sprint mechanical output, lumbopelvic control, and range of motion. Each of the four categories is further divided into clinical tests and field tests. Familiarization was conducted separately for specific tests that were considered to have a learning curve (listed in Table 1). The FHS testing battery was designed to be efficient and mobile, taking only 30 min to conduct per participant, with the clinical tests requiring no general warm-up. A total of nine clinical tests were performed in the following order; two range of motion and asymmetry tests, two posterior chain strength and asymmetry tests, and one lumbopelvic control test. The field tests included sprint mechanical output testing that was combined with the second lumbopelvic control test (The "Kick-back" test during sprinting). These tests lasted seven minutes per participant and required a standardized sprint-specific 15-minute warm-up. Sessions were planned according to the teams' schedules so that there were ideally no matches 72 h before the clinical tests and 96 h before the sprinting tests. Two measurements were obtained and averaged per variable.

All tests are described in more detail in previous work [9]. The test-retest intra-rater reliability of the protocol has been assessed by the same research group and performed by the same clinician (JL). In all 11 tests, inter-day intraclass correlation coefficients (ICC 3,2) ranged from moderate-to-excellent (0.72 – 0.99), and relative reliability (minimal detectable change) ranged between 6.63 – 21.5 % [14].

Two range of motion tests were performed, both assessing between limb asymmetry (Figure 1). The first test was the novel "Jurdan test" followed by the active straight leg raise (ASLR) test. The Jurdan test has never been used in previous injury risk research (Figure 1, A & B). The test aims to consider the influence of the lumbopelvic regions muscles on hamstring extensibility, which has long been proposed to contribute to hamstring strain injuries [16]. Most notably, the iliopsoas has been shown to have the largest magnitude of influence on the hamstrings length during sprinting. Thus, the Jurdan test can be considered a combination of the active knee extension test [12] and the modified Thomas test that is commonly used to assess iliopsoas [17]. As demonstrated in Figure 1, the Jurdan test result is defined as the difference between the shin angle of the actively lengthened leg and the thigh angle of the opposite leg. The ASLR test (Figure 1, C & D) measures the active thigh angle from a straight leg raise and is considered to have good reliability, sensitivity, and specificity [18]. Two range of motion tests were included in the protocol to potentially control for different strain related injury scenarios. The Jurdan test is proposed to be more related to sprinting, while the ASLR more to overstretching actions (e.g., slide-tackling, and high kicks). According to our data, the test outcomes were correlated by r =

0.56. This means that although the results are partly related, they also show clear independence. For both tests, limb angles were measured manually using a validated digital goniometer (Goniometer records, Indian Orthopedic Research Group) [19]. Between-limb asymmetry was calculated using the following formula: (100/maximum value)*(minimum value)*-1*100) as proposed by Bishop et al. [20].

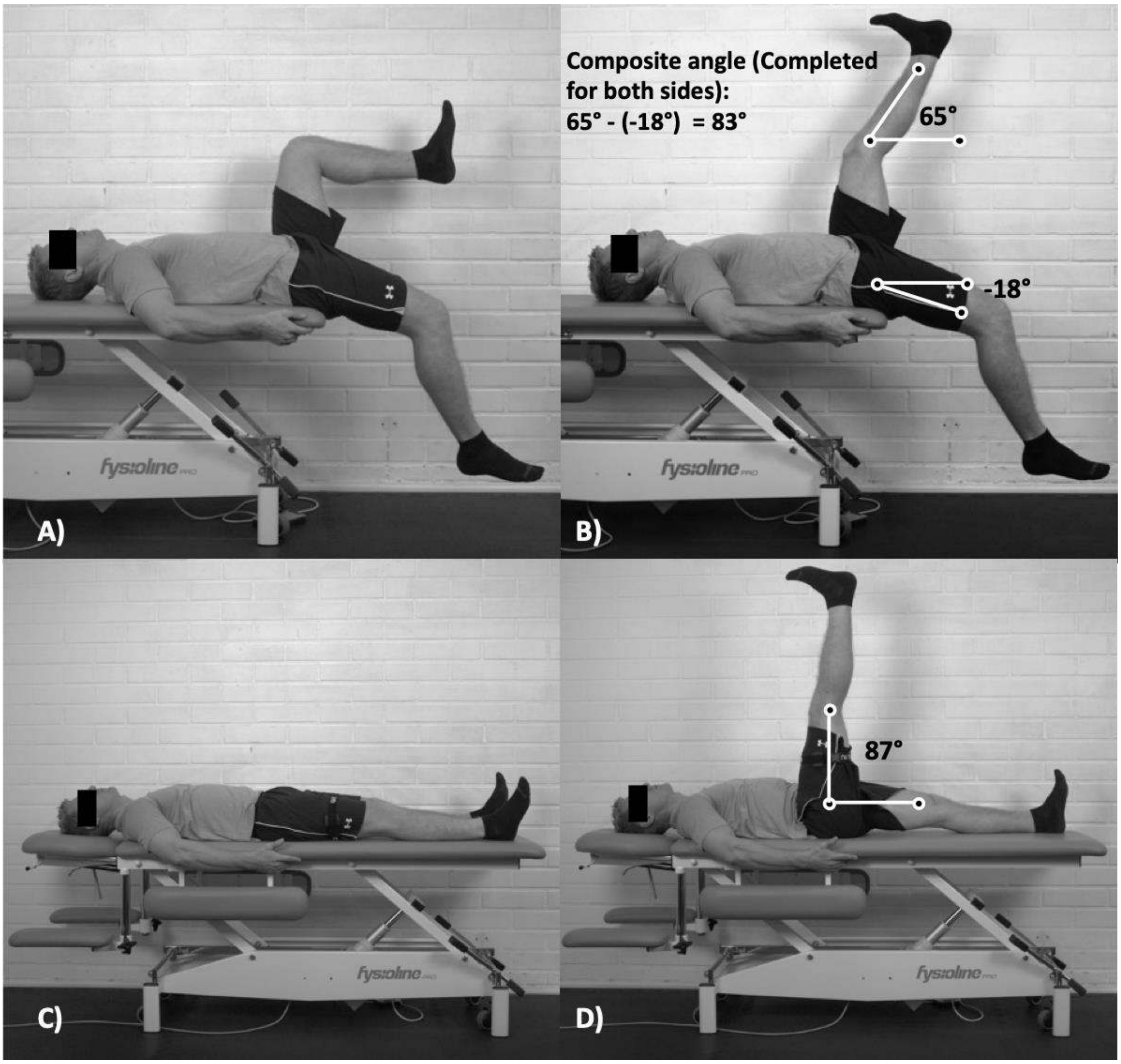

Figure 1. Range of motion tests. The novel Jurdan test (A, B) is based on a composite score from two measurements; the active maximal knee extension angle and the opposite legs passive hip flexion angle. The ASLR test (C, D) is based on the maximal active straight leg hip flexion angle. Asymmetries are calculated from both tests. Therefore, a total of four tests are analysed within the range of motion category. Figure used with permission from Lahti et al. [14].

Two lumbopelvic control tests were performed, including the “Walk test” followed by the sprint technique “Kick-back” test (Figure 2). The latter test was completed in combination with sprint mechanical output testing. The Walk test (Figure 2, A & B), consisted of measuring the peak dynamic sagittal and frontal plane pelvic movement in normal gait by placing a gyroscope sensor on the S1/L5 junction (LetSense Group, Castel Maggiore, Italy) [21]. The second lumbo-pelvic control test “Kick-back” is new to the literature and aims to indirectly assess lumbopelvic control by measuring the thighs interaction in upright sprinting (Figure 2, C & D). This thigh interaction may be related to the degree of anterior pelvic tilt in sprinting [22], which has been associated with increased risk of HMI [23]. The thigh angle was analyzed with open access video analysis software (Kinovea, v.0.8.15) from two adjacent steps within two sprints using a high framerate slow motion camera (Iphone6, Apple Inc, Cupertino, Ca).

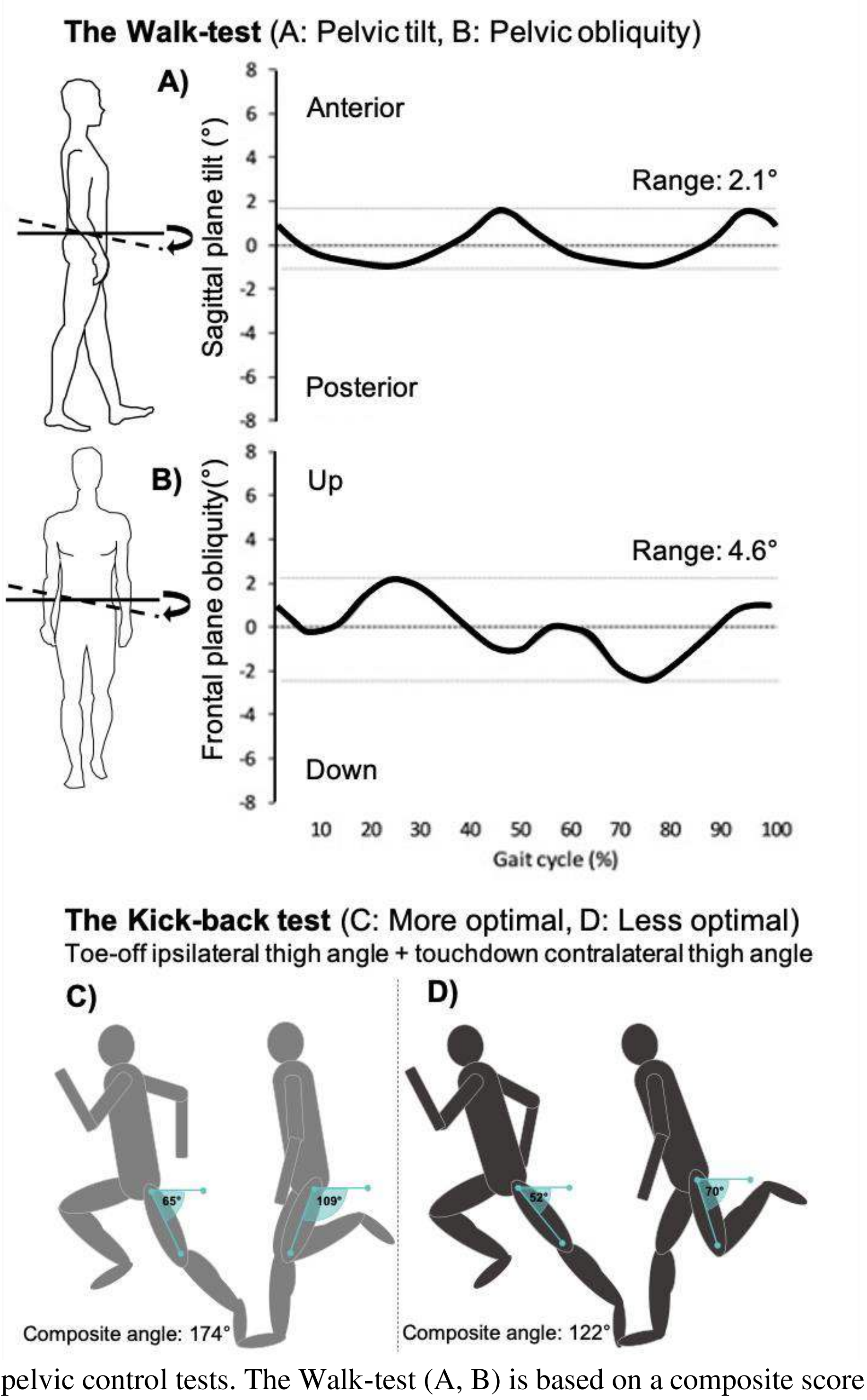

Figure 2. Lumbopelvic control tests. The Walk-test (A, B) is based on a composite score of the sagittal and frontal plane kinematic range of the pelvis during walking. The novel Kick-back test (C, D) is based on a composite score from two measurements; the ipsilateral thigh angle during toe-off and the contralateral thigh angle touchdown. Figure used with permission from Lahti et al. [14].

Limb strength and asymmetry was investigated using two isometric posterior chain strength tests (Figure 3). The first one consisted of an isometric knee flexor strength test, while the second one was a hip extensor strength test; both tested using a hand-held dynamometer (microFET IITM, Hoggan health industries, Draper, UT, USA). Both test positions have been reported to be reliable in previous literature [24,25]. Between-limb asymmetry was calculated with the same method as mentioned in the range of motion section [20].

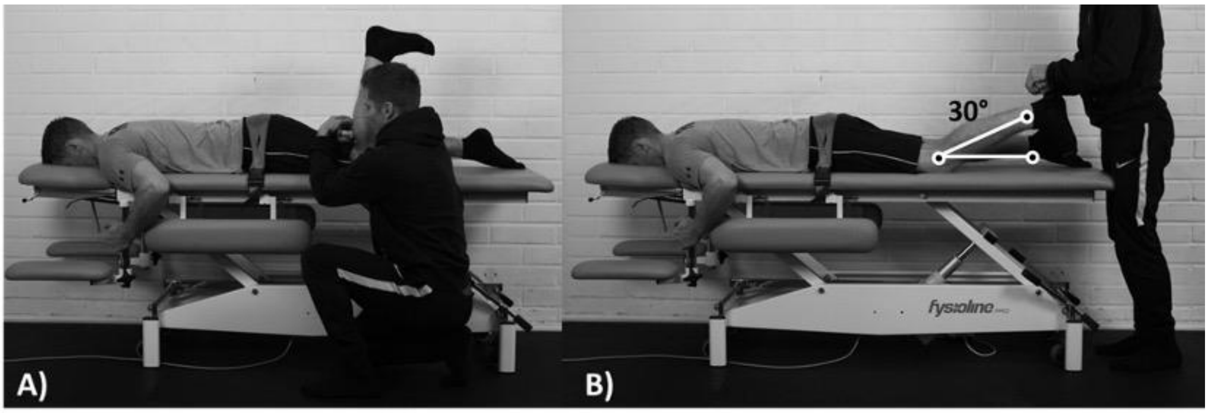

Figure 3. Posterior chain strength tests. The hip extensor strength test (A) and the knee flexor strength test (B) measure strength via a maximal voluntary isometric contraction using manual dynamometry. Asymmetries are calculated in both tests. Therefore, a total of four tests are analysed within the posterior chain strength category. Figure used with permission from Lahti et al. [14].

Sprint mechanical output was assessed by measuring theoretical maximal horizontal force (F0) from two 30-m maximal sprints (Figure 4). Participants were granted three minutes of rest in between both maximal trials. Measurements were performed after a structured warm-up, including approximately 5-min jogging, 5-min dynamic stretching, 1-2 minutes of sprint drills, and 2x10m and 2x30m sprints with increasing intensity, and with small variations according to teams. To standardize tests and improve reliability, all sprints were completed outdoors on synthetic turf in calm weather (wind speed <2.5 m.s-1). To improve the reliability of the 2D sprint kinematics assessment (investigating lumbo-pelvic control), participants were instructed to run along the field line. F0 was computed using a validated field method measured with a radar device (Stalker ATS Pro II, Applied Concepts, TX, USA) [26]. Briefly, inverse dynamics is used to calculate F0 using the time-motion data of the center-of-mass. An exponential function is fitted on the raw velocity–time data. The instantaneous data is combined with system mass (body-mass) and aerodynamic friction to compute the net horizontal antero-posterior ground reaction force. Thereafter, individual linear sprint force–velocity profiles are extrapolated to specify F*0*.

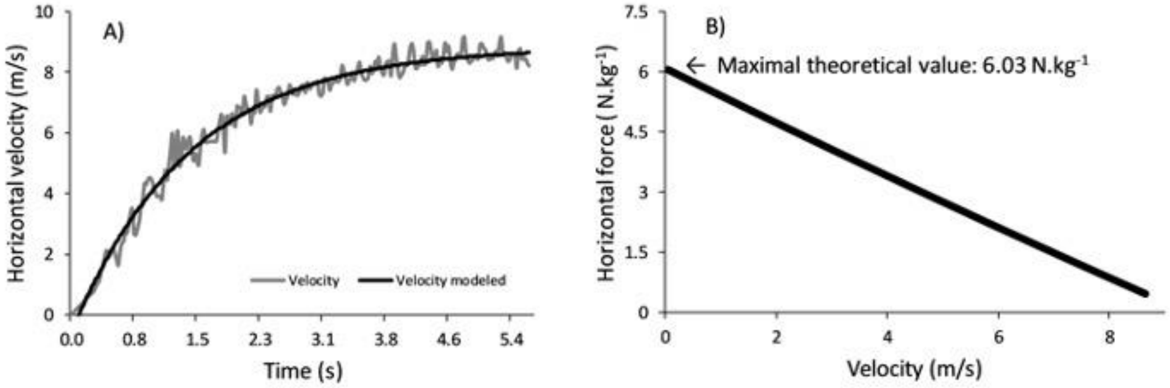

Figure 4. Sprint mechanical output. Raw velocity data from a radar gun is fitted with an exponential function (A). Thereafter, a sprint force-velocity profile is created (B). The variable of interest is the extrapolated maximal theoretical horizontal force value (In figure B it is 6.03 N.kg^{-1}). Figure used with permission from Lahti et al. [14].

Sport exposure and injury data collection

Sport exposure was defined as average weekly training volume (expressed in hours and at group level) and match time (expressed in playing hours at individual level) and collected by the team's strength and conditioning coach.

Injury was defined as any musculoskeletal lesion (sustained through trauma or overuse) occurring during a scheduled training session or official match and causing absence from the next training session or match [27]. Injury data were collected and registered by each team's physiotherapist using a standardized report form including various information (e.g., date, circumstances (match/training), injury location, type, cause, and date of return to play). The primary outcome of this study was the HMI occurrence, which is defined as an injury located at the posterior side of the thigh and involving muscle tissue [28]. Hamstring injuries described as cramping/spasm by the physiotherapist (in absence of an actual structural lesion/tear), were included as muscle injuries in our work. This was due to the absence from playing time related to these functional hamstring injuries. The diagnosis was made clinically and confirmed by ultrasound or MRI. To avoid any rehabilitative attempts of correcting functional asymmetries detected at the pre-season testing, neither players nor their physiotherapists were informed about the results of the entire screening protocol before the completion of the study.

Data analysis

Descriptive analysis was performed for sport exposure, player characteristics, injuries, and screening test results. Categorial variables were reported as frequencies with percentage distributions and continuous variables were reported as the mean with standard deviations (± SD). Injuries were reported as total number of HMI, HMI incidence (per 1000 hours of training, match and total football exposure) and burden of HMI (days lost due to HMI per 1000 hours of exposure).

Then, the population was divided into non-injured (i.e., players who did not sustain any HMI during the entire season) and injured groups (i.e., players who sustained an HMI during the whole season). An independent t-test was used to assess the potential differences between non-injured and injured groups. In addition, a paired t-test was used to test for possible differences between pre- and mid-season testing among all players who performed the two screening tests. For both of the mean comparison approaches described above, effect sizes were calculated, which were subsequently qualitatively interpreted as small (≥ 0.2), moderate (≥ 0.6), large (≥ 1.2), very large (≥ 2.0), and nearly perfect (≥ 4.0) effects [29].

Univariate Cox proportional hazards regression (or Cox regression) with a 'time-to-event' approach was adopted to analyze the association between tests scores and HMI occurrence. Time to the first event was analyzed using a time scale consisting of total hours of football exposure (i.e., training and matches). The cox regression was adjusted for team, age, height, body mass, and history of previous HMI during the last two seasons. The hazard ratio (HR) with a 95% confidence interval (95% CI) are presented for each variable. The assumption that the HR was constant over time was tested. Two models were used, with the first model using the screening tests values at the start of the season and new HMI occurring during the entire season as the outcome, similar to previous literature [12,30]. The second model aimed to account for changes in screening variables during the season [10,11], and thus included HMI occurring between the pre- and mid-season (shorter period), leading to a cut-off point of 90 days (mean time between the pre- and mid-season screening sessions; 94 days, CI95%: 92.2 – 97.2). The researcher who performed the cox regression analyses (PE) was independent of football groups and did not conduct the measurements.

Significance was accepted at $p<0.05$. Analyses were performed using Excel (Office, Microsoft®, 2017) and R (version 3.6.3., © Copyright 2016 The Foundation for Statistical Computing (Comprehensive R Archive Network, http://www.R-project.org)).

RESULTS

Population and exposure

Within the sample of 161 potential football players, one entire team (18 players) was excluded due to incorrect injury data collection, another team (25 players) was excluded due to preseason scheduling issues that led to not completing clinical tests, 16 players had ongoing rehabilitation (all teams), five players switched teams during the season, and two players did not complete sprint testing. Consequently, the final sample considered for data and statistical analyses consisted of 95 professional football players (age: 24.9 ± 5.33 years; body-height: 181 ± 7.11 cm; body-mass: 77.0 ± 7.39 kg), all competing in the Finnish premier league.

This sample's total exposure time throughout the season of interest was 26479 hours (24822 training hours and 1657 match hours). The mean training session exposure and match exposure per player were 264 ± 39.1 hours and 21.5 ± 1.74 hours, respectively, during the 28 weeks of official competition. 73% of the 95 players who completed the pre-season screening session also completed the mid-season screening session (n = 69). The other players were not available due to ongoing injuries (n = 14) and scheduling issues (international matches, n = 9, misunderstanding of testing timetable, n = 2).

Hamstring injuries

There were 17 new HMI, including three that occurred after mid-season screening session. The majority of HMI occurred during sprinting (70%) and involved the Biceps Femoris Long Head muscle (80%). Incidence of HMI was 8.50 injuries per 1000 match hours and 0.47 injuries per 1000 training hours (total injury incidence: 0.76 per 1000 hours). HMI burden was 14.1 days per 1000 hours of football exposure. More information on HMI occurrence is presented in Table 2.

Table 2. Number, prevalence, incidence, and nature of all HMI

HMI occurrence (*n*, % of the population)	
During season	20 (24)
New injuries	17 (18)
Reinjuries	3 (3)
Previous injuries (last two seasons, %)	23 (24)
HMI Injury incidence per 1000 h (CI95%)	
Total injury incidence	0.76 (0.45 – 1.22)
Injury incidence, training	0.47 (0.31 – 0.79)
Injury incidence, match	8.50 (5.21 – 13.7)
Injury severity (*n*, % of HMI)	
Mild (4-7 days)	4 (20)
Moderate (8-28 days)	13 (65)
Severe (>28 days)	3 (15)
Position (*n*, % of new HMI)	
Defender	5 (29)
Midfielder	6 (35)
Forward	6 (35)
Circumstances (*n*, % of HMI)	
Match	11 (55)
Training	9 (45)
Mechanisms (*n*, %)	
Sprinting	14 (70)
Change of direction	3 (15)
Slide tackle	2 (10)
Unknown	1 (5)
HMI time-loss and injury burden (CI95%)	
Days of absence/injury	18.5 (14.0 – 22.9)
Injury burden (1000 h of football exposure)*	14.1 (6.30 – 27.9)

*: Total HMI injury incidence x days of absence from HMI

Changes in screening results during the season

Screening results from both pre- and mid-season session are presented in Table 3. From the total of 69 players completing pre- and mid-season screening session, there was a significant increase in knee flexor strength (3.77 vs 3.99 $N.kg^{-1}$, $p < 0.0001$, ES: 0.35) and maximal theoretical horizontal force (7.63 vs. 7.84 $N.kg^{-1}$, $p = 0.004$, ES: 0.35), and a significant decrease in ASLR asymmetry (6.75 vs 4.36, $p = 0.0001$, ES: -0.60) when comparing the pre- and the mid-season results.

Table 3. Player characteristics and screening tests results from the Football Hamstring protocol

		Comparison between non-injured and injured groups (preseason)				**Comparison between players completing both pre- and mid-season testing**			
Categories	**Variables**	**Non-injured (*n* = 78, CI95%)**	**Injured (*n* = 17, CI95%)**	**p value**	**Effect size**	**Pre-season testing (*n* = 69, CI95%)**	**Mid-season testing (*n* = 69, CI95%)**	**p value**	**Effect size**
Player information	Age	24.6 (23.4; 25.8)	26.4 (24.3; 28.4)			24.95 (23.8; 26.1)			
	Weight	1.80 (1.79; 1.82)	1.82 (1.78; 1.84)			1.81 (1.79; 1.83)			
	Height	77.0 (75.3; 78.7)	76.9 (73.7; 80.1)			77.11 (75.5; 78.7)			
	Previous injury, n (%)	11 (14.0)	6 (35.2)			12 (100)			
Lumbo-pelvic control	Walk test (°)	8.88 (8.35; 9.42)	8.85 (7.67; 10.0)	0.96	-0.01	8.79 (8.26; 9.32)	8.57 (8.12; 9.0)	0.48	-0.10
	Kick-back test (°)	146 (144; 149)	143 (137; 149)	0.24	-0.31	146 (143; 148)	145 (143; 148)	0.62	-0.01
Posterior chain strength	Knee flexor strength ($N.kg^{-1}$)	3.78 (3.64; 3.93)	3.75 (3.46; 4.03)	0.83	-0.06	3.77 (3.63; 3.90)	3.99 (3.84; 4.13)	<0.0001*	0.35
	Knee flexor strength asymmetry (%)	6.40 (5.27; 7.53)	8.11 (5.42; 10.8)	0.22	0.32	6.64 (5.55; 7.74)	7.56 (6.00; 9.10)	0.26	0.15
	Hip extensor strength ($N.kg^{-1}$)	4.16 (3.97; 4.35)	4.35 (4.05; 4.66)	0.38	0.26	4.26 (4.08; 4.44)	4.42 (4.24; 4.61)	0.07	0.19
	Hip extensor strength asymmetry (%)	7.46 (6.20; 8.72)	6.48 (4.22; 8.74)	0.51	-0.19	7.67 (6.41; 8.93)	8.05 (6.57; 9.52)	0.29	0.06
Range of motion	ASLR (°)	87.5 (85.7; 89.3)	86.4 (82.3; 90.5)	0.64	-0.12	88.7 (86.8; 90.5)	88.0 (86.2; 89.9)	0.28	-0.07
	ASLR asymmetry (%)	6.18 (5.20; 7.17)	7.04 (4.42; 9.61)	0.51	0.17	6.75 (5.72; 7.78)	4.36 (3.67; 5.05)	0.0001*	-0.60

	Jurdan test (^{o})	79.1 (76.7; 81.5)	77.0 (70.4; 83.7)	0.50	-0.17	79.40 (76.7; 82.1)	80.2 (77.2; 82.7)	0.44	0.07
	Jurdan test asymmetry (%)	7.53 (6.13; 8.94)	7.01 (4.36; 9.71)	0.77	-0.08	7.18 (5.83; 8.54)	8.39 (6.84; 9.95)	0.26	0.18
Sprint mechanical output	Maximal theoretical horizontal force (N.kg^{-1})	7.67 (7.54; 7.80)	7.46 (7.18; 7.74)	0.22	-0.35	7.63 (7.50; 7.76)	7.84 (7.71; 7.97)	0.004*	0.35

^{o}: degrees, ASLR: Active straight leg raise, N: Newton, kg: kilogram, *: $p < 0.05$

Association between screening tests and HMI risk

The results from the two univariate models of the cox regression are presented in Table 4. The first cox regression model showed no significant association between any screening test and increased HMI risk, including each HMI occurring during the entire season. In the second model, which accounted for injuries that occurred between pre- and mid-season measurements (therefore only including HMI occurring throughout the first half of the season), lower F*0* was significantly associated with HMI occurrence (hazard ratio [HR], 4.02 (CI95% 1.08 to 15.0, p=0.04) (Table 4). No other variable changes between pre- and mid-season testing reached significance in function of HMI occurrence. However, a trend was established for higher pre-season hip extensor strength being associated with increased risk of HMI (Table 4).

Table 4. Cox regression results

Cox regression for all HMI during season (n = 17)

Categories	Tests	Univariate analysis			
		HR	95%CI	p Value	TI (p-value)
Lumbo-pelvic control	Walk test	0.97	(0.78 to 1.20)	0.78	0.28
	Kick-back test	0.97	(0.92 to 1.02)	0.26	0.31
Posterior chain strength	Knee flexor strength	1.46	(0.58 to 3.65)	0.42	0.20
	Knee flexor strength asymmetry	1.04	(0.93 to 1.16)	0.53	0.27
	Hip extensor strength	1.93	(0.94 to 3.95)	0.07	0.24
	Hip extensor strength asymmetry	0.97	(0.87 to 1.08)	0.56	0.22
Range of motion	ASLR	0.97	(0.91 to 1.04)	0.43	0.27
	ASLR asymmetry	1.07	(0.96 to 1.19)	0.25	0.25
	Jurdan test	0.99	(0.94 to 1.05)	0.83	0.06
	Jurdan test asymmetry	0.99	(0.91 to 1.08)	0.85	0.27
Sprint mechanical output	Maximal theoretical horizontal force (F*0*)	2.98	(0.98 to 9.07)	0.06	0.13

Cox regression for all HMI between pre- and mid-seasons screening session (within 90 days) (n = 14)

Categories	Tests	HR	95%CI	p Value	TI (p-value)
Lumbo-pelvic control	Walk test	0.88	(0.68 to 1.12)	0.29	0.06
	Kick-back test	0.99	(0.94 to 1.05)	0.69	0.05
Posterior chain strength	Knee flexor strength	1.45	(0.52 to 4.06)	0.48	0.07
	Knee flexor strength asymmetry	1.05	(0.93 to 1.19)	0.44	0.14
	Hip extensor strength	2.32	(1.00 to 5.37)	0.05	0.16
	Hip extensor strength asymmetry	0.96	(0.85 to 1.09)	0.53	0.11
Range of motion	ASLR	0.97	(0.90 to 1.04)	0.39	0.14
	ASLR asymmetry	1.07	(0.94 to 1.20)	0.31	0.14
	Jurdan test	0.98	(0.93 to 1.04)	0.60	0.05
	Jurdan test asymmetry	0.98	(0.89 to 1.08)	0.66	0.13
Sprint mechanical output	Maximal theoretical horizontal force (F*0*)	4.02	(1.08 to 15.0)	0.04*	0.09

HMI: Hamstring muscle injury, ASLR: Active straight leg raise, *: $p < 0.05$.

DISCUSSION

The main findings of this study revealed that 1) no screening test in isolation was associated with a new HMI occurring during the entire season, and 2) lower maximal horizontal force production capacity (F0) was significantly associated with increased HMI risk when assessing injuries that occurred between the pre- and mid-season testing sessions.

The finding that no screening test in isolation was associated with a new HMI during the entire season was foreseeable based on previous literature [5,6,8,31]. Studies exploring the association between modifiable intrinsic risk factors in isolation and HMI occurrence have shown conflicting results or are limited [5]. The most evident reason is likely due to the difficulty of controlling for the complex nature of injury etiology [32]. Including large samples that have been tested in a multifactorial format is considered of high importance, as it allows for the use of multivariate statistical models [31,32]. In turn, this may allow to answer whether the screening protocol itself is effective, instead of focusing on the potential relevance for specific tests in isolation. However, other considerations are likely also important, such as controlling for changes of tests during the season and increasing the precision of tests [12,17,23].

The potential value of including F0 into screening and monitoring practices

Our pilot study demonstrated that there may be additional strength-related outcome measures sensitive to identify players with increased HMI risk, other than the generally proposed strength measures. The hamstrings have been identified as essential protagonists in contributing to the horizontal force component of the ground reaction force vector (i.e. accelerating the center of mass forward) in sprinting [33,34], which is where most hamstring injuries take place [2,15]. This premise is supported by a recent modelling study, which was the first study to model muscles contribution to the majority of the sprint acceleration phase [34]. The authors reported that the hamstrings functioned as an essential accelerator through the entire sprint alongside thetriceps surae and gluteus medius [34]. The target with hamstring strength testing is to gain insight of the possible load tolerance of the biarticular hamstrings [35]. Thus, tests that assess force output during dynamic actions that emphasize both hip extension and knee flexion mechanical effort could be of interest. Therefore, it was the interest of this study was to test whether measuring horizontal force during sprinting could also indirectly characterize the health status of the hamstrings within their contribution to accelerated run. Specifically, an association of increased risk was found for low levels of F0 when including injuries between pre- and mid-season screening rounds. The increased accuracy of assessing injuries in closer proximity to testing is supported by previous screening literature [13,36]. F*0* is a macroscopic variable, which reflects the sum of its parts. Thus, it does not give accurate information on the microscopic role of a single part in the system, such as specific muscle forces. However, the practicality of measuring F*0* and its wider use also as a performance measure may outweigh its limitations when used in a multifactorial testing environment. Furthermore, recent developments in technology allows for reliable in-situ quantification of F0 from football training using global positioning devices [37]. This is a promising development from a testing frequency standpoint and should be further explored as it allows screening practices to evolve into a monitoring context. Moreover, horizontal force appears to be trainable in football [38,39]. Consequently, there is emerging evidence that the evaluation of hamstring strength, or rather 'force output', should consist of multifactorial testing (mostly eccentric strength combined with sprint F0 testing, based on contemporary evidence) and with frequent scheduling. Despite the difficulty in recruiting professional football athletes, studies with larger sample sizes are needed to confirm this finding and the associated clinical implications/recommendations.

Accounting for changes in screening results during the season

The limitation of not accounting for changes in screening results during the season in prospective cohort studies assessing HMI risk factors has been discussed in literature [12]. As demonstrated by studies in professional cohorts, clinical and functional test results can substantially change over the course of a competition season [10,11]. When comparing this study's pre- and mid-season data, three outcome measures improved significantly with small to moderate effects (ASLR asymmetry, knee flexor relative force, and F0). However, some caution is warranted in interpreting these results as these changes can be due to normal weekly fluctuations in testing scores caused by measurement error and or fatigue. To improve interpretation, inter-rater test-retest reliability needs to be explored for the screening tests, preferably also in a setting of professional football players.

We additionally analyzed the changes in tests within each team. There were on average three screening test variables that showed moderate to large effect size changes within five out of seven teams (two teams showed no changes). A total of 16 substantial changes were observed. Only five changes were considered as moving in a clinically negative direction (i.e., less force output, range of motion, and increased asymmetry). When observing the team's practices, the positive changes were likely largely due to the constant ongoing efforts of reducing the risk of injuries during the season. Furthermore, nearly all in-season test-outcome changes concerned range of motion and force output variables, which were most regularly addressed during the seasonal training planning according to the coaches of the participating teams. They were considered as the most essential for both injury risk management and performance optimization. Therefore, relatively low player performance capacity at the start of the season may partially explain why most injuries occurred near the beginning of the season. This finding has been established in previous research including other cohorts of professional athletes as well [40]. The team coaches speculated that one explanation for the increased HMI risk in the early season is the heavy preseason loading (i.e., the substantial change in athlete loading when comparing off- and preparation season phases). This preparation phase consisted of a combination of practice matches and pre-season tournaments in this cohort, minimizing the time left to spend on injury risk reduction strategies.

The fact that most existing injury-risk identification-related research does not consist of repeated risk factor screening sessions throughout the season is understandable. Pre-season screening protocols can be potentially fatiguing and time-consuming (especially if tests are completed in separate facilities). Furthermore, high sample size prerequisites and repeated voluminous testing data collection likely require collaboration between multiple research groups to deliver study results with sufficient power [32]. Future studies should aim to account for changes in screening results in even closer intervals or insert continuous monitoring evaluation strategies in their athletic samples. This should include cognitive and emotional data collection next to the commonly adopted clinical and functional musculoskeletal outcome parameters [8].

Strengths and limitations

The main strength of this pilot study was that it considered the multifactorial etiology of HMI in professional football, investigating the role of lumbo-pelvic control, range of motion, posterior chain strength and sprint mechanical output for the HMI risk, while introducing novel tests. The FHS protocol has been successfully implemented in several professional teams after education to physiotherapy and physical conditioning staffs in an ongoing intervention study [9], which supports its feasibility in real-life scenarios. Another strength was that analyses were adjusted for important confounding factors, including football exposure, body-mass, team, age, and history of previous HMI, or the samples were otherwise homogenous (e.g., sport exposure [an average of one match and 5–6 days of training per week], weather, level of play, and resting periods).

The main limitation of this study is the low final sample size, which hinders clear conclusions. With this in mind, while multivariate models have been advised to be used for multifactorial injuries [32], such a regression model including all 11 tests and confounding factors would have required a much larger sample [31]. However, univariate analysis such as in this study is also considered important, as potential associations help to spot relevance of risk factors [32]. Finally, it should be mentioned that advancements in technology may lead to specific devices used in this study to become obsolete. Specific methods used in this study for analyzing the raw data can be considered relatively slow (such as the assessment of F0, or the Kick-back mechanism). Furthermore, achieving highly accurate associations between the chosen lumbo-pelvic tests (i.e., pelvic kinematics during normal gait or indirect 2D analysis during sprinting) and pelvic kinematics during dynamic football actions are unlikely. Direct measurements of pelvic kinematics during maximal sprinting, or other relevant kinematic and spatiotemporal variables measured during football exposure would allow for less extrapolation of inferences. Additionally, separate assessment of the sagittal and frontal plane mechanics should be explored. Thus, constant updates in technology will likely allow clinicians to get accurate results faster within the testing categories of interest.

CONCLUSION

This study demonstrated that no single screening test was associated with increased HMI risk in professional football when considering HMI taking place during the entire season. However, when analyzing hamstring injuries that took place throughout the first half of the season when injury incidence was the highest (before mid-season testing (90 days)), lower F*0* was associated with an increased risk of sustaining an HMI. Thus, there may be potential relevance in frequently monitoring F*0* levels during the season in professional football to further improve HMI risk reduction approaches.

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3.3. ANALYSIS AND CONSIDERATIONS OF THEME I

Study I aimed to explore the construct validity of a novel multifactorial musculoskeletal screening protocol designed for professional football. Unfortunately, the degree of validity of the construct (i.e., the screening protocol) could only be partly explored, as the unexpected loss of sample size dictated changes in statistical models. The loss in sample size (mostly via two teams dropping out from the study, n = 43) led to only univariate analysis being conducted instead of both uni- and multivariable. This meant each test within the screening protocol was studied in isolation instead of as part of a cluster of tests. The univariable analysis showed that despite adjusting for confounding factors, no single test was significantly associated with an increased risk of HMI during the entire season ($p > 0.05$). This result is in line with previous hamstring screening literature using similar methods (Pizzari, Green and van Dyk, 2020). However, when the association was explored among HMI closer to the screening round (~90 days), lower F*0* showed a significant association for a higher risk of injury (n = 14, Hazard ratio: 4.02, CI95%: 1.08 - 15.0, p = 0.04). This corresponds to previous findings by Dauty *et al.*, (2016), who showed that strength variables were limited in their association to injury after 3 months. As can be observed from the confidence intervals, the degree of increased risk associated with a lower F*0* was likely overfitted (CI95%: 1.08 - 15.0) due to the low sample size. Thus, caution is warranted in concluding the hazard ratio literally, which showed that there was a 4-fold risk of sustaining an HMI for every 1 $N.kg^{-1}$ drop in F*0*. Yet, considering the low sample size, this does show initial promise for the association strength of F*0* in monitoring practices (Bahr and Holme, 2003), which is confirmed also in lower level cohorts (Edouard, Lahti, *et al.*, 2021).

Despite the lack of multivariable analysis, the study provided multiple valuable results for future research. Although univariable analysis is a reductionist approach (i.e., failing to capture the complex nature of injuries), it is still considered useful for determining initial relevance of a variable for multivariable approaches (Ruddy *et al.*, 2019). The screening protocol used in this study was built upon such information. This means that each testing category was considered important for further research based on earlier findings, which are presented in the thesis' theoretical background. Relevance can also be missed, for example, due to lack of sample size (Ruddy *et al.*, 2019), changes of variables during the season (Lolli *et al.*, 2020), or lack of measurement sensitivity and specificity (Wiesinger *et al.*, 2021). In terms of sample size, study I had a low sample compared to previous literature (n = 95), with multiple studies including samples over 300 players (Arnason *et al.*, 2004; Hauge Engebretsen *et al.*, 2010; van

Dyk, Bahr, *et al.*, 2018; van Dyk, Farooq, *et al.*, 2018). To detect variables that have moderate to strong associations in prospective cohort studies, it is suggested that 20–50 injury cases are required (study I had 17 index HMI). For small associations to be detected, up to 200 injury cases may be required (Bahr and Holme, 2003). This is why it is important for smaller studies, such as ours, to share data so that datasets can be combined for future verification (Ruddy *et al.*, 2019).

However, even with a large sample size, relevance can be potentially missed with univariable approaches due to the complex non-linear nature of injuries (Bittencourt *et al.*, 2016; Ayala *et al.*, 2019). Even conventional multivariable approaches can suffer from the same issue (Ruddy *et al.*, 2019), therefore more advanced machine learning approaches are likely the topic of the future (Ayala *et al.*, 2019; Ruddy *et al.*, 2019). Nevertheless, even with advanced statistical models, testing frequency needs to be constantly improved to control for changes in test performance during the season (van Dyk, Bahr, *et al.*, 2018; van Dyk, Farooq, *et al.*, 2018). Study I showed that some screening variables changed substantially during the season, incuding F*0* (ES: 0.35, $p < 0.05$), which supports the importance of considering injuries closer to the screening. Furthermore, substantial changes in musculoskeletal variables during the season could take place as frequently as every mesocycle (month) (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020), or even microcycle (week) (Rowell *et al.*, 2018). Recently, a highly interesting development has been made to allow for higher testing frequency for F*0*. Morin *et al.*, (2021) showed that calculating F*0* from global positioning system data during football training to be reliable, which can be considered to be an "in-situ" measurement (Morin *et al.*, 2021). This could be considered a crucial development, as players can be tested on a microcycle basis without technically "testing them". The results from study I demonstrated that the availability of players was still a problem, with only 71 % of players being available for the second round of testing. With more frequent testing, availability of important data will likely be improved. Finally, the specificity and sensitivity of each invidual test needs to be constantly developed (Wiesinger *et al.*, 2021). This takes place by both improving testing standardization and creating more precise tests that relate to the injury scenarios. For example, although analysing 2D sprint kinematics and pelvic kinematics from normal gait can be of value, a highly sought after update would likely be inertial measurement units that allow for in-situ kinematic measurements (i.e., measuring during sport exposure). This would potentially allow at some point for coaches to make real-time decisions on changes in injury risk. Another option would be to assess similar simple kinematics from more invasive tests such as repeated sprint ability. Multiple studies have shown that fatigue induced by sprinting can change the running kinematics so that it may increase the risk of HMI (Small *et al.*, 2009; Baumert *et al.*, 2021; Wilmes *et al.*, 2021).

Another important result of this study was establishing the epidemiology of injuries in the chosen cohort, and whether it matched current literature in other cohorts. As the data collection was only done during one season it was important for the results to be highly similar. The burden of HMI has been shown to be around 13-19 days lost per 1 000 player hours in other cohorts (Ekstrand *et al.*, 2011, 2013; Ekstrand *et al.*, 2016; Tabben *et al.*, 2021) and the current study had a highly similar value of 14.1. Also, similar to previous literature, there was a severalfold higher incidence of HMI during matches compared to training (Bjørneboe, Bahr and Andersen, 2014; Ekstrand *et al.*, 2016), most injuries took place during sprinting (Woods *et al.*, 2004; Ekstrand *et al.*, 2012), and most injuries were of moderate severity (8-28 days) (Ekstrand *et al.*, 2011, 2012; Ekstrand *et al.*, 2016; Tabben *et al.*, 2021). The incidence of match injuries in study I was slightly inflated compared to previous literature (8.10 incidence per 1000 match hours). This was likely due to the higher training-to-match ratio found in this cohort compared to other cohorts (Ekstrand *et al.*, 2016; Tabben *et al.*, 2021). Despite the reduced amount of matches, the hamstring muscles were the most frequent injury in this cohort, accounting for 24.4 % of all injuries (not reported in study I), corresponding to previous literature (Witvrouw *et al.*, 2003; Fousekis *et al.*, 2011; Ekstrand *et al.*, 2013; Tabben *et al.*, 2021). In Figure 24, we calculated as additional data the incidence and severity of the top-10 injuries similar to Figure 3 obtained from Bahr, Clarsen and Ekstrand, (2018). Figure 24 results corresponds to the injury burden findings of Ekstrand *et al.*, (2013).

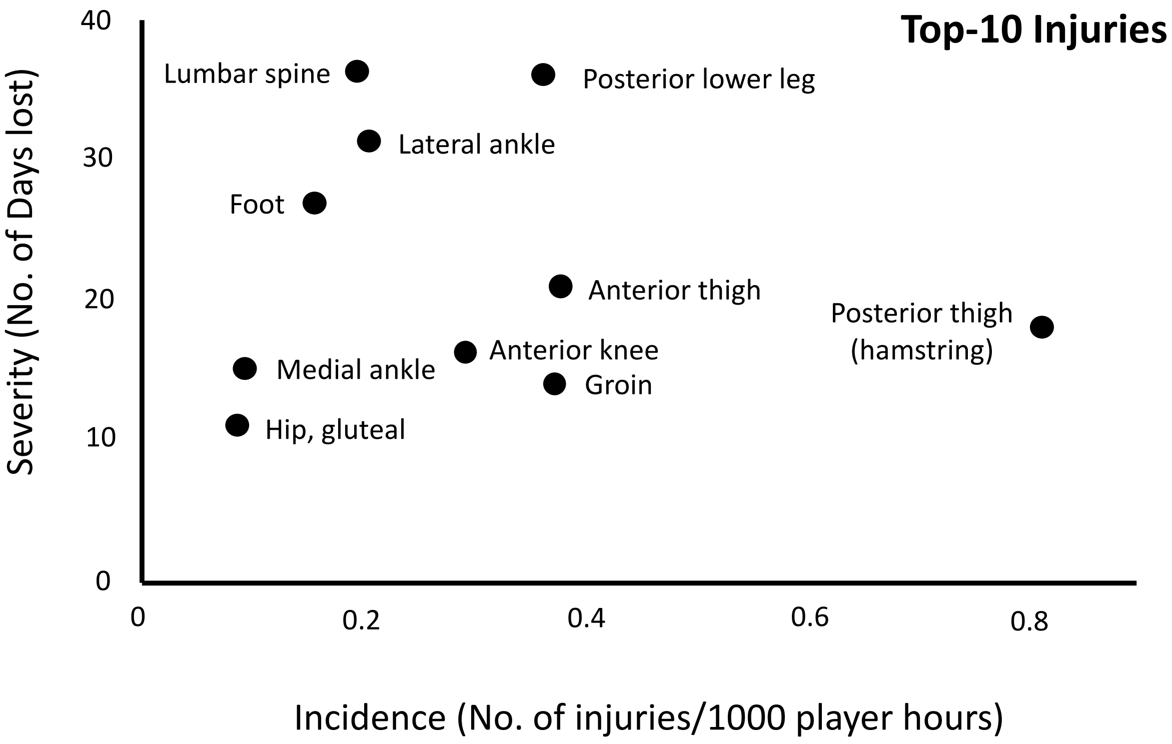

Figure 24. Top-10 injuries in the cohort of study I and their corresponding severity and incidence level.

It should be mentioned that interpretation of changes of test scores from study I should ideally be completed in conjunction with a large sample test-retest inter-rater reliability study. This was unfortunately not in the scope of the thesis. The priority was to first see whether there was a sign of initial construct validity. Efforts were made to improve reliability by averaging two repetitions, which showed initial potential to improve test-retest reliability based on our intra-rater pilot study in an amatuer football cohort (Lahti *et al.* 2021). However, at least for now, we cannot exclude that some changes in variables were nothing more than random between-session variations.

Finally, the surprising result of higher hip extension strength approaching significance for being associated with increased risk of HMI within ~90 days of screening should be discussed (p = 0.05). Stronger performance being a risk factor for certain muscle groups is nothing new in literature. Excluding antagonist performance testing (e.g., H:Q ratio), team-sport prospective cohort studies have also shown that increased performance in certain lower-body strength or power tests can be associated with increased injury risk (Henderson, Barnes and Portas, 2010; Hietamo *et al.*, 2021). In terms of increased HMI risk, Henderson, Barnes and Portas, (2010) showed that increased counter-movement jump power was associated with increased risk of HMI in a multivariable model. One possible explanation is that more powerful players could potentially achieve higher velocities, which would increase the energy absorption requirements of the hamstring muscles (Dorn, Schache and Pandy, 2012). Age can be a confounding factor, as increased age is typically associated with increased injury risk (Pizzari, Green and van Dyk, 2020), and older players may be more powerful due to their higher levels of experience (Henderson, Barnes and Portas, 2010). However, study I controlled for age, and we found no correlation between age and hip extensor strength or maximal velocity. Another possible explanation may that players that are faster as a consequence of increased maximal strength may be at higher risk if they also have unsustainable movement in dynamic actions (i.e., poor running mechanics) (Pfeifer *et al.*, 2018; Hietamo *et al.*, 2021). Although we assessed only one movement proficiency variable (the kick-back mechanism), no correlation was found for this either. It should be mentioned that in study I, hip extensor testing (including asymmetry) had the lowest relative reliability of all tests (Appendix 1, Table 1). This was not the case in our pilot study with a lower-level football cohort. This is likely due to the increased strength levels in professional players, making it challenging for clinicians to maintain a reliable measurement position with manual dynamometry (Figure 19). Consequently, although higher hip extension strength levels approached significance for association with increased risk, the potential lack of reliability makes interpretations difficult. Therefore, improved reliability via other hip extension strength testing options should be explored in future studies while keeping in mind the principles of the presented screening protocol (Figure 18).

To conclude, no variable within the musculoskeletal hamstring screening protocol was associated with increased injury HMI risk during the entire season. When assessing the association between the screening tests and HMI taking place closer to the screening round (between screening round 1 and 2, ~90 days), F*0* was significantly associated with increased risk of HMI. The importance of considering injuries closer to the screening is supported by F*0* increasing significantly during the season. As the sample size was low, the results show potential for F*0* having strong relevance in HMI management. The epidemiology of injuries in the Finnish cohort matched that of previous hamstring literature, and therefore can be considered as an appropriate environment for risk reduction interventions. Future studies should verify the value of the screening tests, including reliability, and validity via univariable and advanced multivariable statistical models.

4. THEME II, IMPROVING HORIZONTAL FORCE CAPACITY IN PROFESSIONAL FOOTBALL

4.1. RESPONDING TO THE SECOND RESEARCH QUESTION

When aiming to change current practices in professional sport such as football, a substantial practical challenge is finding enough space for additional training, especially resistance training. It has been shown that resistance training in non-collision team sports, such as football, is less prioritized during the weekly microcycle compared to collision team sports (Cross *et al.*, 2019). This may not only be a result of sport requirements, but also differences in training culture. Recently, there has been growing interest in using F*0* as an additional variable to monitor hamstring health status (Mendiguchia *et al.*, 2014; Mendiguchia *et al.*, 2016; Morin and Samozino, 2016; Edouard *et al.* 2021). This may allow an opportunity to test performance and risk status at the same time. Initial intervention data indicates that F*0* can be modified within amateur football using a form of horizontally oriented strength training; heavy resisted sprint training (Morin *et al.*, 2017). The logic behind using heavy resisted sprint training for improving F*0* is that F*0* represents strength capacities at low velocities (Morin and Samozino, 2016; M. R. Cross *et al.*, 2018; Cahill, Oliver, *et al.*, 2019). Therefore, heavier resistance may be more specific for this aim (Lahti, Jiménez-Reyes, *et al.*, 2020). In literature, the magnitude of resistance that qualifies a resisted sprint load as 'heavy' remains ambiguous. From a kinematic perspective, a traditional definition might lend itself towards a loads that create a perceivable change in acute running form when compared to unresisted sprinting (e.g., increased leaning due to the sled harness, or stepping more behind center of mass etc.). While the conceptual comparison between resisted and unresisted sprinting, and associated underlying methodology, are debated in in recent literature (Cahill, Cronin, *et al.*, 2019), the threshold delineating heavy and light loads arguably exists around a velocity loss (VL) of more than 10% (Alcaraz *et al.*, 2008, 2019; Alcaraz, Elvira and Palao, 2014). Contrastingly, from a mechanical perspective, loads of up to 50% VL exist toward the 'velocity' end of the horizontal FV (Cross *et al.*, 2018), and accordingly could be classified as 'light' or velocity dominant loads relationship (i.e., target force production at high velocities, and late acceleration phases) (Cahill, Cronin, *et al.*, 2019). Clarification on these points is needed in the research.

Resisted sprint training can be considered a mobile form of resistance training, as it can be relatively easily implemented on-field in conjunction with football specific training. In turn, this may improve its likelihood of implementation within a congested football microcycle. However, it is still unknown whether the same is feasible in a professional cohort where initial levels of F*0* have been shown to be higher (Haugen, Breitschädel and Seiler, 2020). Thus, the feasibility of finding enough space within the microcycle for innovative training approaches that may elicit true change in F*0* and sprint performance needs to be explored. Thus, this created our second question of the thesis:

2) Is F0 trainable within a professional football setting?

This in turn created the second aim of the thesis mentioned in the aims section:

1. To explore whether F*0* (maximal theoretical horizontal force, a variable of the screening protocol) is trainable in professional football players via conducting a resisted sprint training intervention in a professional club setting.

This led to the forming of study II, which succeeded in recruiting two professional football teams within the premier Finnish football league (N = 32), i.e., the same league as study I. The intervention was conducted during the pre-season, including one training match per week during most weeks in both teams (team schedules found in Appendix 2, intervention team: Table 2.1, control team: Table 2.2).

Based on earlier experiences within two separate team sports cohorts (including football and rugby players), we expected that improvements in F*0,* and thus sprint performance, would likely depend on the players initial levels of sprint performance (Cross *et al.*, 2018; Lahti, Jiménez-Reyes, *et al.*, 2020). Therefore, study II aimed to control for this confounding factor by dividing players within the intervention groups based on their initial sprint performance. Unsurprisingly, randomization was not possible within the two professional teams, as the control teams coaching staff did not want to commit to systematic resisted sprint training, and the intervention teams coaching staff did not want to have some players in a control group. However, an important element to increase the validity of the intervention was to compare teams that were highly homogenous in performance. This was difficult to control for, as we had to find a team that wasn't conducting any resisted sprint training and had similar player levels (based on anecdotes, usually teams with similar budgets). The control team that accepted to be in the study had highly similar initial sprint performance (intervention team mean 30-m split-time: 4.64 s, vs Control team mean: 4.63 s, p = 0.88).

To improve interpretation of the results, the resistance provided by the sleds were standardized to a specific velocity loss (VL) from maximal velocity for each player in the intervention groups. As surface friction can highly influence the net resistance provided by the sled, measuring running velocity instead of the absolute load is more accurate for standardizing a specific target stimulus (Cahill, Oliver, *et al.*, 2019; M. R. Cross *et al.*, 2019).

Study II also included secondary aims. One secondary aim was to gain more insight of what type of heavy resistance magnitude should be used when aiming to improve early acceleration performance via targeting to change underlying mechanical properties (e.g., horizontal force capabilities and ground reaction force orientation capability). Thus, the intervention team was further divided into two intervention groups with slightly different heavy resistance magnitudes. One heavy resisted load used previously in literature is a 50% VL load (M. R. Cross *et al.*, 2018), which is considered as the sprinting velocity at which horizontal mechanical power peaks (Cross *et al.*, 2017). Thus, we wanted to replicate this stimulus with a ”velocity-based” approach of sled load programming (Weakley *et al.*, 2021). It should be mentioned that as power is scalar, therefore does not have direction, ”horizontal mechanical power” is not mechanically correct and can be considered a pseudo Newtonian variable (Vigotsky *et al.*, 2019). However, we used this terminology to simplify the concepts for coaches and players data interpretation. The second load was targeted to be heavier to potentially further bias improvements in early acceleration. Based on our pilot data (unpublished), we observed that resistance inducing a VL above 60 % easily led to unwanted kinematic changes in numerous players, such as large magnitudes of ankle dorsiflexion, rotation of the body, and made the sprints look more like walking. Therefore, this led to the study using two heavy resisted loads standardized by either a 50 % VL or 60 % VL. This 10 % difference in maximal running velocity may seem small, but it led to the 50 % VL group having an average resistance of 90 % of body-mass (BM) and the 60 % VL group 120 % of BM (including the weight of the sled). This corresponded to an average difference of 26 kg.

The intervention was planned for 11 weeks (including a two-week taper), with most weeks including two resisted sprint sessions. Some weeks included only one session due to football scheduling conflicts. There was a progression in volume also, with resisted sprints increasing from six to eight per week. To standardize resisted sprint times, the 50 % VL group sprinted for 20-m, while the 60 % VL group sprinted for 15-m (i.e., this way it took them similar times to finish one sprint, and eventually a similar total working time). All sessions finished with a 20-m free sprint.

Outside of the real of sprint performance improvements, another important secondary aim of the study was to answer to preconceptions of the influence of heavy resisted sprint training presented in literature. To clarify, these preconceptions are more or less evidence-guided (but not evidence-based) theories on how the heavy resistance may negatively influence long-term sprint kinematics (Alcaraz *et al.*, 2008, 2019; Alcaraz, Elvira and Palao, 2014). This includes claims such as an excessive increase in trunk angle and in general a more flexed (less stiff) lower limb. As no studies have quantified changes in kinematics after a heavy resisted sprint training intervention, it is unknown whether such claims are factually correct or not. Thus, another secondary aim was to explore whether large kinematic changes took place pre-post intervention by performing basic 2D sagittal plane motion analysis in different phases of the sprint. Additionally, using the same 2D motion analysis, we explored the immediate effect of the heavy resisted sprint loads on kinematics and spatiotemporal variables. This was thought to help interpretation of the long-term kinematic and spatiotemporal results.

4.2. STUDY II: CHANGES IN SPRINT PERFORMANCE AND SAGITTAL PLANE KINEMATICS AFTER HEAVY RESISTED SPRINT TRAINING IN PROFESSIONAL SOCCER PLAYERS.

Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players

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ABSTRACT

Background. Sprint performance is an essential skill to target within soccer, which can be likely achieved with a variety of methods, including different on-field training options. One such method could be heavy resisted sprint training. However, the effects of such overload on sprint performance and the related kinetic changes are unknown in a professional setting. Another unknown factor is whether violating kinematic specificity via heavy resistance will lead to changes in unloaded sprinting kinematics. We investigated whether heavy resisted sled training (HS) affects sprint performance, kinetics, sagittal plane kinematics, and spatiotemporal parameters in professional male soccer players.

Methods. After familiarization, a nine-week training protocol and a two-week taper was completed with sprint performance and force-velocity (FV) profiles compared before and after. Out of the two recruited homogenous soccer teams ($N = 32$, age: 24.1 ± 5.1 years: height: 180 ± 10 cm; body-mass: 76.7 ± 7.7 kg, 30-m split-time: 4.63 ± 0.13 s), one was used as a control group continuing training as normal with no systematic acceleration training (CON, $N = 13$), while the intervention team was matched into two HS subgroups based on their sprint performance. Subgroup one trained with a resistance that induced a 60% velocity decrement from maximal velocity ($N = 10$, HS60%) and subgroup two used a 50% velocity decrement resistance ($N = 9$, HS50%) based on individual load-velocity profiles.

Results. Both heavy resistance subgroups improved significantly all 10–30-m split times ($p < 0.05$, $d = -1.25; -0.62$). Post-hoc analysis showed that HS50% improved significantly more compared to CON in 0–10-m split-time ($d = 1.03$) and peak power ($d = 1.16$). Initial maximal theoretical horizontal force capacity (F0) and sprint FV-sprint profile properties showed a significant moderate relationship with F0 adaptation potential ($p < 0.05$). No significant differences in sprinting kinematics

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or spatiotemporal variables were observed that remained under the between-session minimal detectable change.

Conclusion. With appropriate coaching, heavy resisted sprint training could be one pragmatic option to assist improvements in sprint performance without adverse changes in sprinting kinematics in professional soccer players. Assessing each player's initial individual sprint FV-profile may assist in predicting adaptation potential. More studies are needed that compare heavy resisted sprinting in randomized conditions.

Subjects Anatomy and Physiology, Kinesiology
Keywords Strength training, Resistance training, Sprinting, Velocity-based training, Coordination, Professional sport

INTRODUCTION

Sprinting performance has been shown to be effective in distinguishing different levels of soccer players (*Haugen et al., 2014*; *Cometti et al., 2001*). Accordingly, it makes sense that there exists an interest in finding optimal methods to improve sprint performance in high level settings (*Haugen et al., 2014*). This likely also explains the fact that articles on soccer and sprinting have increased exponentially in the last two decades (*Nikolaidis et al., 2016*). However, there still seems to be a lack of sprint performance intervention articles, especially in professional settings. Therefore, researching the usefulness of different training options for sprint performance enhancement within a professional soccer setting seems warranted.

One option that may provide a beneficial stimulus for sprint performance is resisted sprint training (*Kawamori et al., 2014*; *Bachero-Mena & González-Badillo, 2014*; *Morin et al., 2017*; *Pareja-Blanco, Asián-Clemente & SáezdeVillarreal, 2019*; *Cross et al., 2018*; *Alcaraz et al., 2018*; *Alcaraz, Elvira & Palao, 2014*; *Spinks et al., 2007*; *Cahill et al., 2019*). Different forms of resisted sprint training have been used with the aim to improve sprint performance by overloading different parts of the sprint acceleration phase, both from a intermuscular coordination and structural standpoint (*Cahill et al., 2019*). Recently, there has been a growing interest in exploring the value of heavy resistance in assisting improvements in sprint performance (*Morin et al., 2017*; *Pareja-Blanco, Asián-Clemente & SáezdeVillarreal, 2019*; *Cross et al., 2018*). Based on the available literature, a definitive definition for heavy resisted sprinting does not seem to exist. One definition for heavy resistance could be that it prioritizes within moderation overloading kinetic properties (force application) over kinematic specificity (technical similarity). Thus, this would be considered "specific traditional overload" (*Brearley & Bishop, 2019*). According to cross-sectional biomechanical studies, this corresponds to all loads clearly decreasing maximal velocity capacity more than 10% (*Alcaraz et al., 2008*). This has also been reported to be around a less accurate measure of 7.5–15% of body mass (BM), a method that is highly biased towards frictional components and does not consider the relative strength of the athlete (*Cross et al., 2019*). The idea behind heavy loading is to focus on the early acceleration phase of the Force-Velocity (FV) spectrum. Thus from a kinetic standpoint, the focus is on highly overloading the horizontal component of the resultant ground reaction force vector (Morin et al., 2017; Cotter et al., 2013; Kawamori, Nosaka & Newton, 2013). This stimulus could affect to different degrees both mechanical effectiveness of the ground force orientation during the step (i.e., what ratio of anterior-posterior and vertical forces is the resultant force built upon) and absolute force output, which could lead to improved sprint performance.

Interventions with heavy loads have shown mixed results, possibly to some degree due to different methodology. Four studies showed positive effects on early sprint performance (Kawamori et al., 2014; Bachero-Mena & González-Badillo, 2014; Morin et al., 2017; Cahill et al., 2020), another showed split time improvements between 10–30-m, while instead a lighter load group improved also at 0–20-m (Pareja-Blanco, Asián-Clemente & SáezdeVillarreal, 2019), and one study showed trivial to small effects on performance from both heavy and light resisted sprinting (Cross et al., 2018). Evident methodological differences include large differences in what is considered heavy (range ~20%–50% velocity decrement), not standardizing each subjects load to a specific velocity decrement (using the less accurate % of BM method) (Petrakos, Morin & Egan, 2016), using 1 vs. 2 training sessions per week, initial level and amount of familiarization of subjects, and timing between training completion and post-testing and associated tapering (Morin et al., 2020). Limitations have also been discussed, such as not considering each subjects degree of loading needs in terms of initial sprint FV-characteristics in the start of the study (Cross et al., 2018).

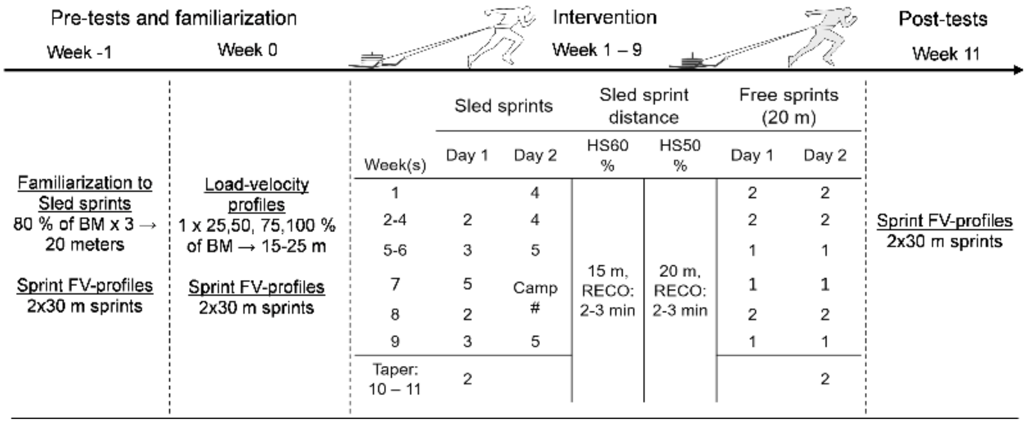
Furthermore, potential negative effects of violating kinematic specificity by using heavy resistance in sprinting have also been discussed in literature (Alcaraz et al., 2018; Alcaraz, Elvira & Palao, 2014; Alcaraz et al., 2019). These discussions have possibly created uncertainty among coaches, with regards to whether such immediate kinematic and spatiotemporal changes would then lead to detrimental long-term transference to unloaded sprinting. One theory is that training with increased loading may lead to excessive trunk lean (Alcaraz, Elvira & Palao, 2014), or create a biomechanically less optimal lower body mechanics, such as excessive flexion (Alcaraz et al., 2019). However, only two intervention studies have addressed the long-term effects of resisted sprint training on technique and both using only light resistance (7.5–10% velocity decrement), while comparing to a unresisted sprint training group (Alcaraz, Elvira & Palao, 2014; Spinks et al., 2007). Despite the light loading, both interventions showed that resisted sprint training led to a very slight increase in trunk lean during initial acceleration, while one of the studies showed that even the unresisted group increased trunk lean (Spinks et al., 2007). Increased trunk lean has been associated with improved force production in the anterior-posterior direction (Atwater, 1982), thus making it less clear when it is a unwanted adaptation and whether it is dependent on the training modality. Therefore, one possible explanation for why the unresisted group in Alcaraz, Elvira & Palao (2014) did not increase trunk lean could be related to the fact that there was no improvement in early acceleration performance, unlike the unresisted group in Spinks et al. (2007). However, adaptations to kinematics should be carefully interpreted to whether it is a cause or an effect and as such may not be directly related.

Therefore, the aim of this study is to investigate changes in sprint performance and the potential underlying mechanical changes (kinematics, spatiotemporal variables, ground force orientation efficiency, and main kinetic outputs) after integrating two different heavy resisted sprint training loading protocols within a professional soccer setting. The aim of the first heavy load is to follow the same maximal mechanical power parameters as in previous literature, which corresponds to a 50% velocity decrement relative to maximal velocity (*Cross et al., 2018*; *Cross et al., 2019*). The aim of the second heavy load is to have a slightly higher focus on maximal strength and early acceleration, which corresponds to a 60% velocity decrement. Our first hypothesis was that both heavy loads will improve early split-time sprint performance, with the heavier load being even more effective at early acceleration. Our second hypothesis was that both loads will increase early acceleration center of mass (CM) distance and CM angle at toe-off.

MATERIALS AND METHODS

Study design and participants

A pre-test versus post-test experimental design utilizing three groups was used to examine the effects of heavy resisted sprint training in professional male soccer players. 32 male professional soccer athletes from two teams in the premier division in Finland volunteered to participate in the study using convenience sampling (age: 24.1 ± 5.1 years: body-height: 180 ± 10 cm, body-mass: 76.7 ± 7.7 kg). The sample size in this study was highly similar to previous resisted sprint training studies using comparable methods (*Alcaraz, Elvira & Palao, 2014*; *Spinks et al., 2007*). Inclusion criteria included being a professional soccer athlete competing within the Finnish Premier soccer league. An exclusion criterion was placed for goalkeepers due to the lower amounts of linear sprinting. No exclusion criterion was placed for age, but under 18-year-old athletes were required to have parental consent. Both teams were in initial pre-season and trained on average of 7–10 sessions per week (which included strength training twice per week) and competed an average of once per week. More detailed scheduling can be found in the Tables S9, S10. One professional soccer team was used as two intervention groups and the other professional soccer team as a control group. The soccer team selected to function as the control group did not train early or late acceleration separately from sport-specific practice in their pre-season protocol, including no resisted sled training. Therefore, they were instructed to continue training as normal. The intervention team was further randomly matched into two homogenous subgroups in terms of sprint performance with different heavy sled loading schemes. These loading schemes corresponded either to a heavy sled (HS) load that decreased the athlete's maximal velocity by 50% (HS50%) or 60% (HS60%). A total of 15 training opportunities were provided within 9 weeks (Fig. 1). Including two training sessions each week was not possible because of the teams scheduling conflicts. This corresponded to 6 out of 9 weeks including two sessions per week. Furthermore, tapering was initiated on week 10 and continued to week 11 where post testing was performed. Therefore, both the control and intervention group were tested for sprint performance and kinematic changes 11 weeks apart. Testing was performed on the same day of the week (end of the week, after



Week(s)	Sled sprints Day 1	Sled sprints Day 2	Sled sprint distance HS60 %	Sled sprint distance HS50 %	Free sprints (20 m) Day 1	Free sprints (20 m) Day 2
1		4	15 m, RECO: 2-3 min	20 m, RECO: 2-3 min	2	2
2-4	2	4			2	2
5-6	3	5			1	1
7	5	Camp #			1	1
8	2				2	2
9	3	5			1	1
Taper: 10 – 11	2					2

Figure 1 **Training program design.** HS: Heavy Sled, *: sled velocity verification was completed on week 1, filming of sled technique on week 2, RECO: recovery time between sprints, m: meters, FV: Force-velocity, #: camp training included two sprints with rubber bands and 2×2 free sprints on separate days.

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a low intensity day), but one week apart. The intervention groups had the opportunity to complete two weeks of pretesting on sprint performance and technique analysis, while due to scheduling issues, the control group was available for one week of testing. All training and testing sessions were completed inside on artificial turf, with an exception made for post testing, which was performed outside on the same type of artificial turf on the same time and day of the week. Wind conditions were still (1 ms^{-1}) on the outdoor post testing day with a highly similar temperature (14 vs. 15 C). Written informed consent was obtained from all athletes on the first day of familiarization, and approval for this study was granted by the University of Jyvaskyla Ethical Committee and was performed in the accordance with the Declaration of Helsinki.

GROUP ALLOCATION

Athletes in the intervention soccer team were ordered from the lowest to highest 30-m split times derived during two weeks of familiarization and, thereafter, matched in a pairwise manner into either of the following heavy sled groups: HS50% or HS60% to balance variance. The best 30-m performance was used from the two familiarization weeks. The 0–30-m split time was used as it has a lower measurement error compared to smaller split-times (*Haugen, Breitschädel & Samozino, 2018*), and because it was the maximal split-time distance used in our testing protocol. There was no ordering of the control group, however, the sprint performance was predicted to be similar due to earlier research collaboration work with the team involving sprint performance testing. The initial aim was to recruit an equal amount of soccer athletes within the control team. However, only 13 were available to volunteer and were considered healthy by the team physiotherapist to perform sprint testing at this point of the early pre-season. The final group size and respective highly homogenous 30-m performance times were the following:

HS60%, $N = 10$, 4.65 s, 95% CI [4.55–4.77] vs. HS50%, $N = 9$, 4.62 s, 95% CI [4.56–4.69] vs. CON, N: 13, 4.63 s, 95% CI [4.55–4.70], $p = 0.88$.

Testing procedures and data analysis

Sprint Force-Velocity profile and performance tests

Following warm-up, all participants completed two 30-m maximal sprints from a standing stance start. The passive recovery between sprints was three minutes. Sprint performance (split times 0–5, 0–10, 0–20, and 0–30-m), kinetic outputs and mechanical efficiency were computed pre- and post-training from the best time trial. Data was derived from a radar device (Stalker ATS Pro II, Applied Concepts, TX, USA), using a validated field method as reported previously (*Haugen, Breitschädel & Samozino, 2018*; *Samozino et al., 2016*; *Morin et al., 2019*). Individual linear sprint Force-Velocity (FV) profiles in the antero-posterior direction were calculated and thereafter relative theoretical maximal force ($F0$: N.kg^{-1}), velocity ($v0$: m s^{-1}), and maximal power (Pmax: W.kg^{-1}) capabilities. Despite the use of an approximate measurement of "maximal power" , which can be considered a pseudo-power (*Vigotsky et al., 2019*), the term maximal power output will be used in this study. Mechanical efficiency was calculated based on the maximal ratio of forces (RFmax in %) and the average ratio of forces for the first 10-m (Mean RF on 10-m in %). These RF values are a ratio of the step-averaged horizontal component of the ground-reaction force to the corresponding resultant force, i.e., these values aid the interpretation of mechanical effectiveness with which the ground force is oriented in early acceleration (*Morin & Samozino, 2016*). RFmax depicts the theoretical maximal effectiveness of directing force forwards in the first step of the sprint (within the constraints of sprint running stance, the higher the value of RFmax, the more forward, horizontally-oriented the ground push during the stance phase). Mean RF on 10-m focuses on the same parameter, but is an average of the forward force application effectiveness over the first 10-m. A more horizontally oriented ground reaction force was considered beneficial within the range of values reported in this study.

Load-velocity tests

The final sled familiarization session was combined with load-velocity testing. Load-velocity tests were completed using one unresisted and three resisted sprints (50%, 75%, 100% of BM) for both HS groups, outlined in previous literature (*Cross et al., 2017*). Thereafter, individualized load-velocity profiles were created for each athlete with a least-square linear regression (*Cross et al., 2017*). The individual resistance leading to a 60% and 50%-velocity decrement from maximal velocity was calculated.

Sled velocity was verified with the radar on the first week of training to be within a 5% range of the targeted velocity. A total of 3 athletes' loads had to be modified with an increase of 2.5–7.5 kg, that were verified again the following week (Final ranges, HS60%: -58.4%, 95% CI [-59.4–-57.5], HS50%: -49.4%, 95% CI [-51.4–-47.5]).

Sprint spatiotemporal and kinematics assessment

For all FV-profile sprints, video images were obtained at 240 Hz with a smart phone video camera at a HD resolution of 720p (Iphone6, Apple Inc, Cupertino, Ca). The kinematic sprint sequences of interest were the touchdown (first frame the foot was visibly in contact with the ground) and toe-off (first frame the foot had visibly left the ground) across the first extension and three steps of early acceleration and 3 steps in upright sprinting of the sprint using 6× zoom in Kinovea (v.0.8.15), similar to previous literature (*Wild et al., 2018*). The same leg sequence was analyzed pre-post, with a secondary effort to analyze the sequence as close to the midpoint of the camera as possible. The cameras were placed 9-m perpendicular at the 1.5-m mark and the 22.5-m mark along a 0– 30-m line, at a 1.1 m height, allowing approximately a 9-m field of view. 1.5-m was chosen based on that the first three steps have been considered unique to early acceleration (*Von Lieres und Wilkau et al., 2018*), taking place within around three meters in this population. Upright mechanics were analyzed at 22.5-m based on that team sport athletes are at around 95% or at maximal velocity at this phase (*Clark et al., 2019*).

Furthermore, an additional data analysis was performed in the second week of the study to observe the immediate effects of the resisted sprint training on early acceleration mechanics. The second week was chosen so that the athletes had time to react to the used coaching cues, which are defined in the intervention section. According to our data, sleds at this resistance magnitude reach maximal velocity around 5-m, therefore going into a velocity maintenance phase for the remaining meters (~10-m for HS60%, ~15-m for HS50%). Thus, this was considered the main stimuli zone for each sprint, and therefore, it was used to compare to early acceleration of the unloaded sprint. This was done by having the sled sprint start 5-m before the calibration zone for unloaded early acceleration.

All filming zones were calibrated to a 5-m horizontal distance along the midpoint of the camera at the line. The human body was modelled as 18 points. This required manual digitization of the following: vertex of the head, halfway between the suprasternal notch and the 7th cervical vertebra, shoulder, elbow, and wrist joint centers, head of third metacarpal, hip, knee, and ankle joint centers, and the tip of the toe.

The following spatiotemporal and kinematic step characteristics were determined after exporting the digitalized coordinates to Excel (Microsoft Office 2016): contact time (s), step length (m; horizontal displacement between initial contact of one foot and the point of initial contact of the opposite foot, measured from the toe tips), and step rate (Hz; calculated as 1/step time, where step time was determined as the sum of contact time and the subsequent aerial time). Whole-body center of mass (CM) location was calculated using *De Leva (1996)* segmental data. This allowed for the calculation of touchdown and toe-off distances (horizontal distance between the toe and the CM, with positive values representing the toe ahead of the CM). Furthermore, angles of the trunk (relative to the horizontal) and the hips (ipsilateral and contralateral) were quantified. All distances of CM were normalized to the height of the athlete and reported as (m/body length) (*Wild et al., 2018*). All sprints were analyzed twice to improve reliability with the digital marker method.

Intervention

Training protocols are outlined in Fig. 1. Familiarization within the intervention group for sled training was initiated two weeks before the training intervention and was combined with the sprint Force-Velocity (FV)-profile tests (2 × 30-m sprints), including group allocation based on sprint performance. A load of 80% of BM (2 × 15-m sprints) was selected for familiarization. A total of 15 heavy resisted sprint training session opportunities were planned within 9 weeks and an additional two-week taper (two sessions total) across the 11-week pre-season. This 11-week interval included a break week in the form of an international training camp. Therefore, resisted sprint training sessions were, in general, twice per week, transitioning from a total of six resisted sprints per week up to eight at the midway point (week 5). All training sessions included 20-m free sprints, which were in the start of the program two per session, transitioning to one free sprint per session after the midway point. All athletes were harnessed at their waist, using the 21 kg sprint sleds (DINOX, customized sled, Finland). To standardize the stimuli between athletes within both intervention subgroups, a velocity-based training approach was utilized, where all athletes used a load that adapted their velocity to the desired threshold. In this case HS60% used a load leading to a 60% velocity decrement from maximal velocity and HS50% used a load leading to a 50% decrement from maximal velocity. The 50% load was chosen to simulate power properties as it has been shown that external maximal power is reached approximately at 50% of maximal velocity in a maximal acceleration sprint (*Cross et al., 2017*). The heavier 60% velocity decrement load was chosen with the aim to stay within proximity to the 50% load but stimulate more maximal strength properties, thus an even higher bias towards early acceleration. On the artificial training surface, this 10% velocity difference corresponded to the average relative mass of 120% of BM in the HS60% group and 94% of BM in the HS50% group (including the mass of the sled), equating to a group average difference of 26 kg. A sled sprint distance of 0–15-m for the HS60% group and 0–20-m for the HS50% group was used to standardize sprint time (HS60%: 4.26 s, 95% CI [3.74–4.77], HS50%: 4.73 s, 95% CI [4.39–5.08], $p = 0.15$). Training was supervised by the team strength and conditioning coach and completed after the warm-up for technical and/or tactical training on field. Pre-training warm-up (~15 min) included light running, dynamic full-body stretches, muscle and dynamic movement pattern activation, and low to high intensity sprint exercises. Between-sprint rest was three minutes. Both groups were given the same coaching cues, that is, prioritizing stride power (or push) over stride frequency and high arm movement with aligned posture. Finally, post testing was completed at the end of a two-week tapering period, by reducing the modality specific volume down from eight sprints a week to two, with one session of two free sprints per week.

Statistical analysis

Shapiro–Wilk's test was used to test the data's normality and levene's test was used to examine the homogeneity of variance. A 3 × 2 (group × time) repeated-measured ANOVA with Bonferroni post-hoc comparisons was used to determine the within- and between-group effects as well as examining interaction effects. Baseline measures were used as covariates to control for the effect of initial sprint performance. Sprint performance was defined mechanically (Pmax, F*0*, RFmax, Mean RF on 10-m, v*0*, and Sprint FV-profile), by split-times (5-m, 10-m, 20-m, and 30-m), spatiotemporally (contact time, step rate, step length at initial acceleration and maximal velocity), and kinematically (hip angle, trunk angle, CM distance). For each individual the sprint with the best 30-m time within pre and post testing was compared statistically for both mechanical-, split times- and sprint technique variables. Independent and paired two-tailed t-tests were used to analyse within- and between-group differences of the immediate effects of the resisted sprint training on early acceleration mechanics (two groups). Given the large number of analyses (26), we adjusted for multiple comparisons using the Benjamini–Hochberg procedure utilizing a false discovery rate of 0.05 (*Benjamini & Hochberg, 1995*). Effect sizes (ES) were calculated using pooled SD and interpreted with Hopkins' benchmarks to distinguish small ($\geq$0.2), moderate ($\geq$0.6), large ($\geq$1.2) effects (*Hopkins, 2002*). Accounting for typical fluctuations in athletes' weekly sprint performance and sprint technique was of interest in our study. Thus, minimum detectable change (MDC) with 95% confidence intervals was calculated from the difference in best performance sprint FV-profile variables completed during pre-test week -1 and 0 (*Lahti et al., 2020*). The sprint with the best 30-m time was used for kinematic and spatiotemporal variables. MDC was derived using Typical Error (TE) $\bullet$ 1.96 $\sqrt{2}$, and MDC% was defined as (MDC/$\bar{X}$) $\bullet$ 100. Test-retest reliability for each variable analyzed was assessed by intraclass correlation coefficient ($ICC_{3,1}$), coefficient of variation (CV%), TE with 95% confidence intervals, and MDC, using Hopkins spreadsheet (*Hopkins, 2017*). ICCs were defined as poor (ICC <0.40), fair (0.40 $\leq$ ICC <0.60), good (0.60 $\leq$ ICC <0.75), and excellent (0.75 $\leq$ ICC $\leq$ 1.00). Alpha was set at $p < 0.05$. Descriptive data are presented as mean ± standard deviation (SD).

RESULTS

A total of four subjects could not complete the required pre-post measurements. Due to sustaining a flu, one athlete within the HS60% group could not perform final testing, making a total of nine out of 10 subjects completing the protocol. Due to injuries, three subjects in the control group could not participate in the post testing, making a total of 10 subjects measured. Furthermore, although participating in the sprint performance measurements, there was one camera malfunction during the HS50% group post-testing, leading to a loss of pre-post kinematics of one subject.

Out of 15 possible sessions, within the 9-week window the HS60% completed an average of 10.6 (95% CI [9.57–11.54]), while HS50% completed an average of 10.3 (95% CI [9.30–11.37]). For HS60%, this corresponded to a resisted sprint volume of 38.2 (95% CI [35.5–40.9]) and for HS50% 37.4 (95% CI [34.2–40.7]), $p = 0.72$.

Group Characteristics at Baseline

All variables were normally distributed. For the final sample completing the study, baseline population variance was not significantly different for any variables, including age, height, mass, kinetic and kinematic variables ($p > 0.09$), with all split-times being highly similar (Table 1, $p > 0.55$).

Reliability

All reliability statistical values can be found in supporting information (Tables S1–S8), including MDC%, TE, CV% and ICC. For the sprint FV-profile and performance variables, within and between session ICC ranged from good to excellent (0.60 –0.98, 95% CI [−0.09–0.99]), except for sprint FV-profile slope and mean RF on 10-m, with RF on 10-m showing

Table 1 **Results for sprint split-times.**

		Within-group statistics					**Between-group statistics**
Kinematic variables MAX	**MDC (%)**	**Group**	**Pre (SD)**	**Post (SD)**	**% Δ (95%CI)**	***P*-value (post-hoc), ES**	
5-m split time (s)[a]	0.06 (4.00)	HS60%	1.39 (0.05)	1.35 (0.04)	−2.54 (−3.56; −1.52)	$p = 0.05$, ES: −0.74	NS
		HS50%	1.39 (0.04)	1.34 (0.04)[**]	−3.14 (−5.63; −0.65)	$p = 0.005$[**], ES: −1.04	
		CON	1.38 (0.04)	1.36 (0.04)	−0.90 (−2.17; 0.88)	$p = 1.00$, ES: −0.33	
10-m split time (s)[a,b]	0.06 (2.78)	HS60%	2.15 (0.08)	2.09 (0.06)[**]	−3.05 (−4.07; −2.03)	$p = 0.001$[**], ES: −0.96	HS50% >CON, $p = 0.03$[*], ES: 1.03
		HS50%	2.14 (0.06)	2.07 (0.06)[**]	−3.37 (−5.29; −1.46)	$p < 0.001$[**], ES: −1.25	
		CON	2.12 (0.06)	2.10 (0.04)	−0.87 (−1.95; −0.52)	$p = 0.76$, ES: −0.37	
20-m split time (s)[**]	0.06 (1.71)	HS60%	3.45 (0.12)	3.36 (0.10)[**]	−2.45 (−3.37; −1.54)	$p = 0.008$[**], ES: −0.77	NS
		HS50%	3.43 (0.08)	3.32 (0.10)[**]	−3.07 (−4.64; −1.51)	$p < 0.001$[**], ES: −1.15	
		CON	3.41 (0.09)	3.37 (0.08)	−1.10 (−2.22; −0.03)	$p = 0.44$, ES: −0.47	
30-m split time (s)[a]	0.07 (1.50)	HS60%	4.65 (0.17)	4.56 (0.14)[*]	−2.04 (−3.03; −1.06)	$p = 0.021$[*], ES: −0.62	NS
		HS50%	4.62 (0.10)	4.49 (0.12)[**]	−2.89 (−4.15; −1.64)	$p < 0.001$, ES: −1.18	
		CON	4.62 (0.12)	4.56 (0.11)	−1.23 (−2.47; −0.26)	$p = 0.33$, ES: −0.48	

Notes.

HS, Heavy sled; CON, Control; s, seconds; Hz, Hertz; ES, Effect size (Small: 0.2–0.59, Moderate: 0.60–1.19, Large 1.19 >); SD, Standard deviation; Δ, alpha (change pre post); NS, Nonsignificant.

[a] Significant main effect of time.

[b] Significant group × time interaction effect.

[*] Significant post-hoc difference pre- to post-intervention ($p < .05$).

[**] ($p < 0.01$).

poor between session reliability (0.23, 95% CI [−0.57–0.81]), and FV-profile slope showing fair reliability (0.49, 95% CI [−0.33–0.89]). For the reliability of the digitization process (within sprint spatiotemporal and kinematic variables), ICC was excellent (0.83 –0.99, 95% CI [0.38–0.99]). For the within and between session spatiotemporal and kinematic variables, ICC ranged from fair to excellent (0.41 –0.99, 95% CI [0.03–0.99]), except for maximal velocity contact time, showing poor within-session reliability (0.34, CI: −0.37; 0.80).

Between and within group statistics

Body mass

No significant differences were found at baseline and pre and post for BM in the 3 groups ($p > 0.05$).

Sprint Split-times

All descriptive and inferential statistics for sprint performance can be found in Table 1 and visualized in Fig. 2. All split-times showed significant main effects for time ($p < 0.05$). Post-hoc analyses revealed significant improvements in both HS60% and HS50% for 10-m (HS60%, $p = 0.001$, $d = -0.96$; HS50%, $p < 0.001$, $d = -1.25$), 20-m (HS60%, $p = 0.008$, $d = -0.77$; HS50%, $p < 0.001$, $d = -1.15$), and 30-m split-times (HS60%, $p = 0.02$, $d = -0.62$; HS50%, $p < 0.001$, $d = -1.18$) after controlling for baseline performance. HS50% was the only group to significantly improve 5-m split-time ($p = 0.005$, $d = -1.07$), although a trend was present for HS60% ($p = 0.05$, $d = -0.74$). However, only 0–10-m, 0–20-m, and 0–30-m split time improvements surpassed the between-session minimal detectable change threshold (Fig. 2). This means that the changes in 5-m split-times could be due to normal weekly fluctuations in performance combined with measurement error. A group × time interaction effect was observed for 10-m split-time ($F(2,24) = 4.031$, $p = 0.031$). Post-hoc analysis revealed that 10-m split-time improved significantly more in HS50% compared to CON over the study period ($p = 0.03$, $d = 1.03$).

Sprint Force-Velocity profile variables

All within- and between-group statistics for mechanical variables can be found in Table 2. Correlations between mechanical variables can be found in Fig. 3. All mechanical variables showed significant main effects for time ($p < 0.05$). Post-hoc analyses revealed significant improvements in both HS60% and HS50% for $F0$ (HS60%, $p = 0.02$, $d = 1.00$; HS50%, $p = 0.002$, $d = 1.04$), Mean RF on 10-m (HS60%, $p = 0.013$, $d = 0.80$; HS50%, $p < 0.001$, $d = 1.14$), and Pmax (HS60%, $p = 0.011$, $d = 0.84$; HS50% , $p < 0.001$, $d = 1.18$) after controlling for baseline values. However, the $F0$ changes (HS60%: 7.83%, HS50%: 9.23%) were under the between-session minimal detectable change threshold (9.53%). RFmax improved significantly in all groups (HS60%, $p = 0.011$, $d = 1.25$; HS50%, $p = 0.001$, $d = 1.01$; CON, $p = 0.041$, $d = 0.55$). There was a significant improvement in HS50% for $v0$ (Δ 3.08%, $p = 0.04$, $d = 0.78$), however, the result remained under the between session minimal detectable change threshold (3.13%). No other within-group significant changes were observed ($p > 0.05$). A group × time interaction effect was observed for Pmax ($F(2,24) = 4.055$, $p = 0.030$), and a trend for $F0$ ($F(2,24) = 2.778$, $p = 0.082$).

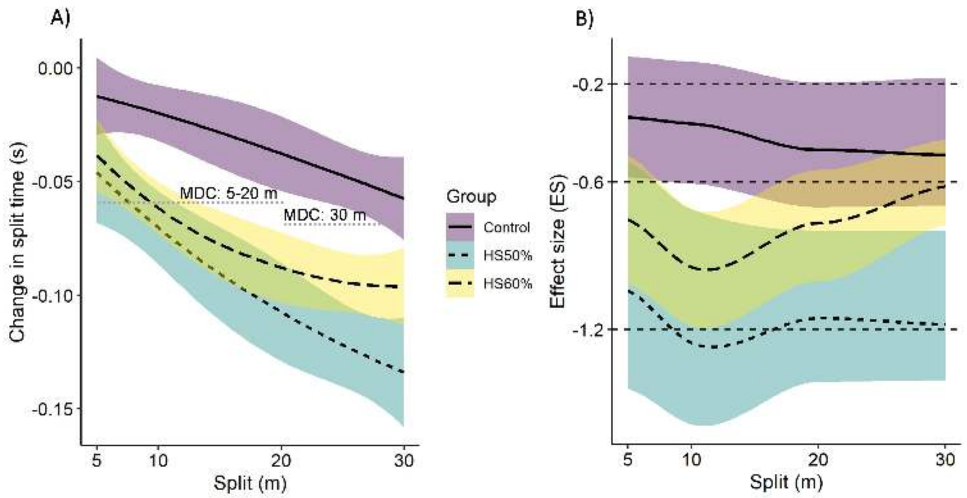

Figure 2 **Sprint split-time changes.** Raw Changes in split time performance with MDC thresholds (A) and their corresponding effect sizes within each group with ES thresholds (B). The lines between the four split-time measurements (0-5, 0-10, 0-20, 0-30) have been smoothed. The error ribbons represent standard error via bias corrected and accelerated bootsrapping at 0.68 confidence intervals, corresponding to +/- 1 standard deviation. HS: Heavy sled, CON: control group, MDC: Minimal detectable change.

Full-size DOI: 10.7717/peerj.10507/fig-2

Post-hoc analysis revealed that Pmax improved significantly more in HS50% compared to CON over the study period ($p = 0.03$, $d = 1.16$). No other between-group differences were observed.

Sprint kinematic and spatiotemporal variables

Cross-sectional analysis of immediate effects of sled on early acceleration. All significant results for immediate effects of sled are visualized in Fig. 4. All descriptive and inferential statistics can be found in Table 3. Due to timetable issues, eight out of nine subjects were available for kinematic filming of the sled from the HS60% group and six out of nine from the HS50% group.

Between-group t-tests showed no differences ($p > 0.05$). Within group t-test comparisons with Benjamini–Hochberg corrections showed that the provided resistance from the sled led to significant changes in both spatiotemporal and kinematic variables. All spatiotemporal variables changed significantly in the HS60% group, with increased contact time ($p = 0.003$, $d = 2.10$), step rate ($p = 0.004$, $d = -1.90$), and step length ($p = 0.008$: $d = -1.58$). Both sled loads significantly decreased touchdown CM distance (HS60%: $p = 0.003$, $d = 1.99$; HS50%: $p = 0.003$, $d = 3.50$) and CM angle at touchdown (HS60%: $p = 0.005$, $d = -2.30$, HS50%: $p = 0.005$, $d = -3.00$), corresponding to taking steps further behind center of mass. No other variables reached significance ($p > 0.05$).

Pre-Post intervention changes in kinematic and spatiotemporal variables. All descriptive and inferential statistics for sprint technique can be found in Table 4 and visualized in Fig. 5. In early acceleration, there was a main effect for time in step length, contralateral hip angle at toe-off, and contralateral hip angle at touchdown. At maximal velocity, there was

Table 2 Results for sprint mechanical variables.

		Within-group statistics					Between-group statistics
Variable	**MDC %**	**Group**	**Pre (SD)**	**Post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**	
F*0* ($N.kg^{-1}$)[a]	0.68 (9.53)	HS60%	7.23 (0.63)	7.77 (0.42)*	7.83 (4.16; 11.5)	$p = 0.018^{*}$, ES: 1.00	NS
		HS50%	7.27 (0.59)	7.91 (0.65)**	9.23 (3.58; 14.9)	$p = 0.002^{**}$, ES: 1.04	
		CON	7.43 (0.50)	7.58 (0.45)	1.89 (−1.60; 5.39)	$p = 1.00$, ES: 0.30	
RFmax (%)[a]	1.64	HS60%	47.9 (2.57)	50.8 (1.88)*	6.03 (4.01; 8.03)	$p = 0.011^{*}$, ES: 1.25	NS
		HS50%	47.9 (3.51)	51.2 (2.91)**	7.12 (2.59; 11.7)	$p = 0.001^{**}$, ES: 1.01	
		CON	50.1 (2.39)	51.6 (2.58)*	3.00 (0.42; 5.58)	$p = 0.041$, ES: 0.55	
Mean RF on 10-m (%)[a]	4.99	HS60%	27.7 (1.71)	28.9 (1.42)*	4.70 (2.83; 6.58)	$p = 0.013^{*}$, ES: 0.80	NS
		HS50%	27.9 (1.59)	29.8 (1,61)**	6.58 (4.00; 9.17)	$p < 0.001$, ES: 1.14	
		CON	28.6 (1.61)	29.3 (1.36)	3.20 (0.95; 5.45)	$p = 0.05$, ES: 0.65	
Pmax ($W.kg^{-1}$)[a,b]	1.10 (6.97)	HS60%	16.0 (1.66)	17.3 (1.35)*	8.36 (5.11; 11.6)	$p = 0.011^{*}$, ES: 0.84	HS50% vs CON: $p = 0.03^{*}$, ES: 1.16
		HS50%	16.2 (1.31)	18.1 (1.82)**	11.64 (6.40; 16.9)	$p < 0.001$, ES: 1.18	
		CON	16.5 (1.27)	17.0 (1.08)	4.05 (0.94; 7.15)	$p = 0.70$, ES:: 0.49	
v*0* ($m.s^{-1}$)[a]	0.28 (3.13)	HS60%	8.93 (0.51)	9.08 (0.39)	1.79 (−0.21; 3.78)	$p = 1.00$, ES: 0.32	NS
		HS50%	9.03 (0.36)	9.31 (0.33)*	3.08 (1.44; 4.72)	$p = 0.044^{*}$, ES: 0.78	
		CON	8.96 (0.36)	9.10 (0.42)	2.04 (−0.45; 4.54)	$p = 1.00$, ES: 0.34	
Sprint FV-profile (-F*0*/v*0*) [a]	0.06 (7.37)	HS60%	−0.81 (0.08)	−0.86 (0.05)	6.07 (1.54; 10.62)	$p = 0.29$, ES: −0.67	NS
		HS50%	−0.81 (0.08)	−0.85 (0.06)	6.11 (−0.30; 12.5)	$p = 0.57$, ES: −0.60	
		CON	−0.83 (0.07)	−0.83 (0.07)	0.12 (−5.31; 5.56)	$p = 1.00$, ES: −0.06	

Notes.

F_0, Heavy sled; CON, Control; s, seconds; Hz, Hertz; ES, Effect size (Small: 0.2–0.59, Moderate: 0.60–1.19, Large 1.19 >); SD, Standard deviation; Δ, alpha (change pre post); NS, Nonsignificant.

[a] Significant main effect of time.

[b] Significant group ×time interaction effect.

[*] Significant post-hoc difference pre- to post-intervention ($p < .05$).

[**] ($p < 0.01$).

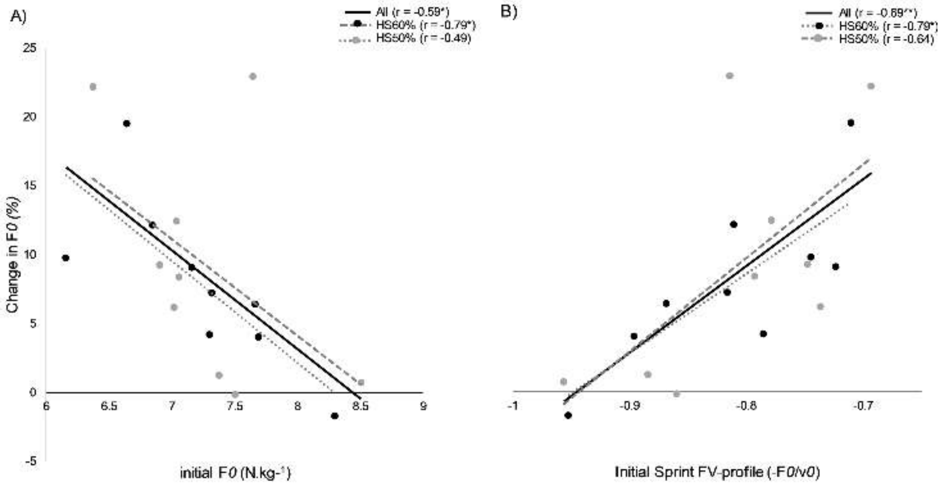

Figure 3 **Mechanical variable correlations.** Correlation coefficients between initial values in (A) maximal theoretical horizontal force (F*0*) production, (B) initial Sprint FV-profile (-F*0*/v*0*), and respective changes post intervention. HS: Heavy sled, CON: control group, *: $p < 0.05$, **: $p < 0.01$.
Full-size DOI: 10.7717/peerj.10507/fig-3

a main effect for time in step rate, trunk angle at toe-off, hip contralateral angle at toe-off, and CM angle at toe-off. Post-hoc analyses revealed a significant decrease in both HS60% and CON for contralateral hip angle at touchdown during early acceleration (HS60%: Δ -4.01%, $p = 0.004$, $d = -0.80$; CON: Δ -3.13%, $p = 0.006$, $d = -0.80$) after controlling for baseline values. However, the result remained under the between session minimal detectable change threshold (5.85%). All other within-group comparisons did not reach significance ($p > 0.05$).

No interaction effects were found for pre and post sprint kinematic och spatiotemporal variables for both early acceleration and upright sprinting ($p > 0.05$).

DISCUSSION

The main results of this study were that, although both heavy load conditions (50% and 60% velocity decrement) improved sprint performance in soccer players, the HS50% was the only group showing changes in sprint parameters that were significantly different from CON. A clear favoring towards improvements in early acceleration performance and sprint kinetics were present in both HS50% and HS60% groups, showing moderate to large effect size differences compared to CON. Furthermore, although both loads produced significant immediate changes in early acceleration at toe-off and touchdown, no long-term changes on early acceleration and upright sprint technique were observed that surpassed the minimal detectable change. These results suggest that heavy resisted sprinting can be successfully integrated in a professional soccer setting, potentially preferably with resistance associated to a ~50% drop in maximal running velocity compared to ~60%.

Our initial hypothesis was partly met, with heavy resisted sprinting leading to improved early acceleration sprint performance. It is important to mention that the reported 5-m within-group improvements fell under the minimal detectable change threshold and, thus,

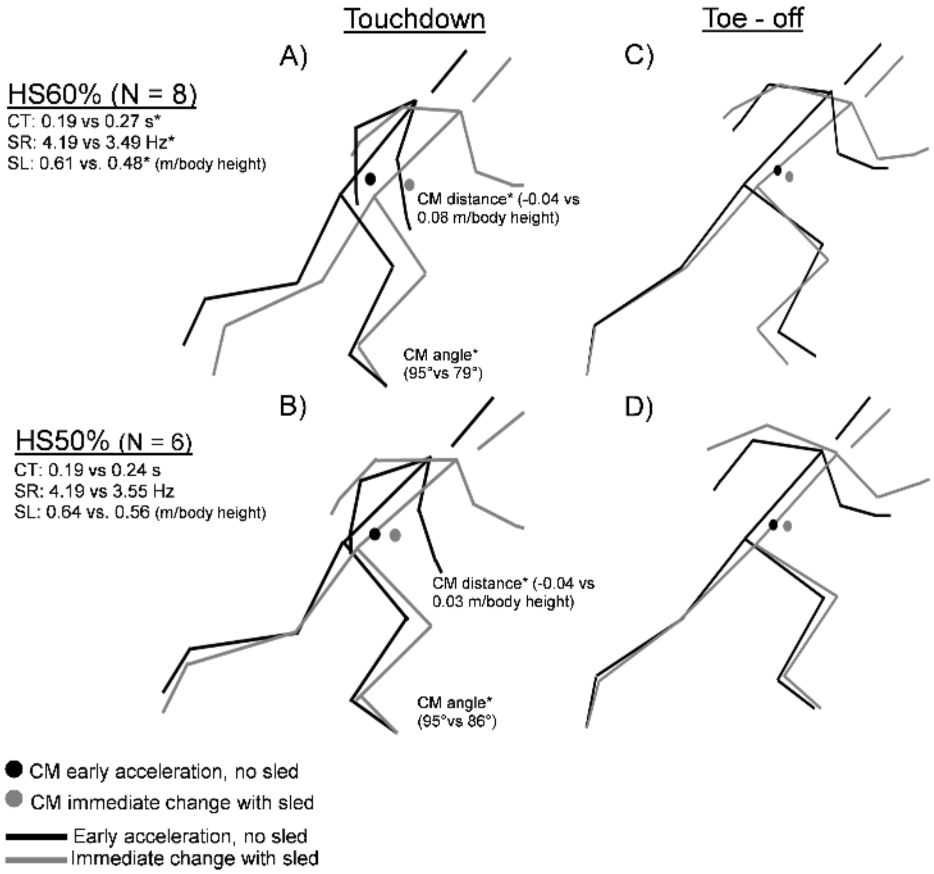

Figure 4 **Sprint kinematic and spatiotemporal changes, immediate effects of sled.** Immediate kinematic and spatiotemporal differences between early acceleration (black) and sled sprinting (gray). Touchdown (A, B) and toe –off (C, D) within HS60% and HS50% groups. HS: Heavy sled, CT: Contact time, SR: Step Rate, SL: Step Length relative to body height, CM: Center of Mass, IPSI: Ipsilateral (ground contact leg), m: meter, *: $p < 0.05$. No group differences were found ($p < 0.05$).

Full-size DOI: 10.7717/peerj.10507/fig-4

still could be interpreted as remaining within the measurement error thresholds (Fig. 2). This is a logical result based on previous literature on 5-m split time measurements (*Bezodis, Salo & Trewartha, 2012*). However, we expected to see differences between the heavy loads in improving specific parts of early acceleration sprint performance. Specifically, we expected the HS60% group to mostly improve the 0–5-m split-times, whereas the HS50% group would mostly improve the 0–10-m split times. This is because the first steps of acceleration are considered to be more dependent on maximal force capacity, with its importance reducing with increasing velocity (*Kawamori, Nosaka & Newton, 2013*; *Cottle, Carlson & Lawrence, 2014*). Hence the larger load was thought to provide a higher transfer in this area. However, both heavy loads had similar effects on early acceleration performance (Fig. 2). Although the HS50% group was the only group to reach significantly lower split-times compared to CON and had a large effect size (0–10-m split-time). Furthermore, Fig. 2 shows trends towards HS50% providing a broader stimulus across the entire acceleration phase. Future studies should verify how reproducible this adaptation signature is. The most evident reasons for the lack of differences in loads can be a combination of a too small difference in loading parameters and that the total training volume was possibly not high enough.

The underlying kinetic reasons to the performance improvements were also of interest in this study. Therefore, we analyzed the ratio of forces at the first step and over the first 10-m (RFmax and mean RF on 10-m). However, caution should be considered within the interpretation of mean RF on 10-m, showing poor between-session reliability within this population. The analysis showed that when considering initial values, there was a lack of clear difference in effect size between RFmax and F*0* compared to the control group (both moderate effects). Therefore, improvements in both their maximal ground reaction force capacity and their capability to orient this force more horizontally may have contributed to improved sprint performance. However, Pmax was the only biomechanical variable to show significant improvements compared to CON, specifically in the HS50% group. As external maximal power is produced at approximately 50% of maximal velocity in a maximal acceleration sprint (*Cross et al., 2017*), it makes sense that Pmax was maximized in the HS50% group. Therefore, the ability to produce higher forces at higher velocities (i.e., maximal mechanical power), seemed to be the main driver for the improved sprint performance.

The most important aim of improving sprint performance was met, an essential part in preparing soccer athletes for the season (*Haugen et al., 2014*; *Cometti et al., 2001*). This contradicted previous literature with similar loading parameters. Specifically, the main methodological strengths of this study compared to previous literature were that the present groups were evenly divided based on their initial sprint performance, training was done mostly 1–2 per week instead of once, and tapering was completed (*Pareja-Blanco, Asián-Clemente & SáezdeVillarreal, 2019*; *Cross et al., 2018*). Furthermore, in the study by *Pareja-Blanco, Asián-Clemente & SáezdeVillarreal (2019)* loads were not standardized and individualized to a specific velocity decrement, but rather to body mass (80% of BM). Therefore, one conclusion is that if a time slot of roughly 20 min is accepted for velocity-based resisted sprint training within field practice conditions 1–2 per week, it will likely be beneficial, assuming the athlete has been assessed for lacking early acceleration capacity (Fig. 4). However, our study did not have a group completing non-resisted sprint training, only a control group completing sport-specific training. Therefore, we do not know if just the mere systematic focus on early acceleration, regardless of load, is enough. Measuring a force-velocity and load-velocity profile for everyone might be an issue for some as there may be time constraints and lack of access to technology. However, this can be done relatively quickly and at a low cost with the help of accurate apps (*Romero-Franco et al., 2017*), while saving some time with a shorter load-velocity protocol (3 loads: 0, 25 and 75% of BM is sufficient to obtain the linear individual load-velocity profile, see Fig. 2 in *Cross et al. (2018)*), although this still needs to be validated.

Our second hypothesis was that both loads would improve early acceleration toe-off CM distance (more triple extension of the body) and CM angle (increased forward body lean). The results showed no changes in the kinematics or any other variables in early acceleration, which is in contrast to previous light load literature showing slight increases in trunk lean

Table 3 Results for kinematic variables from immediate effects on early acceleration of sled loads.

Variable	Group	Toe-off without sled	Toe-off with sled	% Δ ± CI 95%	Within group Statistics (P-value, ES)	Touchdown without sled	Touchdown with sled	% Δ ± CI 95%	Within group Statistics (P-value, ES)
CM distance (m/body length)	HS60%	0.42 (0.04)	0.45 (0.03)	7.74 (−0.53; 16.0)	$p = 0.15$, ES: 0.85	−0.04 (0.03)	0.08 (0.08)	−820 (−1670; 29.3)	$p = 0.003^{*}$, ES: 1.99
	HS50%	0.43 (0.01)	0.46 (0.03)	7.18 (3.31; 11.0)	$p = 0.03$, ES: 1.34	−0.04 (0.02)	0.03 (0.02)	−847 (−1751; 55.9)	$p = 0.003^{*}$, ES: 3.50
CM angle (°)	HS60%	46.8 (1.77)	44.1 (2.21)	−5.79 (−9.90; −1.67)	$p = 0.04$, ES: −1.49	95.3 (4.19)	79.8 (8.59)	−16.1 (−22.9; −11.0)	$p = 0.005^{*}$, ES: −2.30
	HS50%	46.6 (1.22)	44.7 (1.49)	−4.46 (7.41; −1.52)	$p = 0.06$, ES: −2.33	95.2 (3.30)	86.2 (2.60)	−8.46 (−11.0; −5.97)	$p = 0.005^{*}$, ES: −3.00
Hip-angle Ipsilateral (°)	HS60%	171 (7.61)	173 (10.6)	2.05 (−1.91; 6.01)	$p = 0.41$, ES: 0.10	101 (7.30)	108 (20.3)	7.67 (−9.25; 24.6)	$p = 0.40$, ES: 0.41
	HS50%	174 (2.95)	181 (4.82)	4.22 (1.33; 7.11)	$p = 0.07$, ES: 1.70	105 (8.10)	108 (4.04)	3.18 (−1.40; 7.78)	$p = 0.28$, ES: 0.60
Hip-angle Contralateral (°)	HS60%	85.7 (6.72)	90.3 (7.16)	6.01 (−3.30; 15.3)	$p = 0.19$, ES: 0.57	161 (8.81)	159 (13.1)	−0.34 (−6.44; 5.76)	$p = 0.71$, ES: −0.18
	HS50%	86.7 (4.08)	84.7 (6.09)	−3.81 (−7.58; −0.02)	$p = 0.45$, ES: −0.59	164 (6.59)	164 (10.2)	2.56 (−2.08; 7.21)	$p = 0.91$, ES: 0.00
Trunk angle (°)	HS60%	46.3 (5.20)	42.7 (8.37)	−6.09 (−19.0; 6.82)	$p = 0.29$, ES: −0.60	46.8 (6.18)	42.0 (8.11)	−7.54 (−21.2; 6.11)	$p = 0.18$, ES: −0.85
	HS50%	47.9 (2.87)	49.4 (2.76)	1.12 (−4.25; 6.50)	$p = 0.31$, ES: 0.33	49.1 (3.97)	48.4 (2.40)	−1.77 (−6.45; 2.90)	$p = 0.66$, ES: –0.19
Spatiotemporal variables	**Group**	**Early acceleration, no sled**		**Early acceleration, with sled**		**% Δ ± CI 95%**		**Within group Statistics (P-value, ES)**	
Contact time (s)	HS60%	0.191 (0.02)		0.274 (0.05)		40.0 (24.5; 55.4)		$p = 0.003^{*}$, ES: 2.10	
	HS50%	0.193 (0.01)		0.240 (0.04)		28.2 (13.3; 43.1)		$p = 0.03$, ES: 1.71	
Step Rate (Hz)	HS60%	4.19 (0.20)		3.49 (0.51)		−16.5 (−23.3; −9.70)		$p = 0.004^{*}$, ES: −1.90	
	HS50%	4.19 (0.17)		3.55 (0.41)		−14.8 (−23.6; −6.12)		$p = 0.041$, ES: −2.09	
Step Length (m/body length)	HS60%	0.61 (0.06)		0.48 (0.10)		−21.9 (−32.3; −11.5)		$p = 0.008^{*}$, ES: −1.58	
	HS50%	0.64 (0.04)		0.56 (0.04)		−11.3 (−16.7; −5.97)		$p = 0.02$, ES: −.2.00	

Notes.

HS, Heavy sled; CON, Control; TO, Toe-off; TD, Touchdown; CM, Center of Mass; m, meter; s, seconds; Hz, Hertz; ES, Effect size (Small: 0.2–0.59, Moderate: 0.60–1.19, Large 1.19 >); SD, Standard deviation; Δ, alpha (change pre post).

*Significant difference after controlling for multiple comparisons using the Benjamini–Hochberg procedure.

Table 4 Results for kinematic and spatiotemporal variables in early acceleration (ACC) and upright sprinting (MAX).

		Within-group statistics									
Kinematic variables ACC	**MDC (%) Toe-off**	**MDC (%) Touchdown**	**Group**	**ACC Toe-off pre (SD)**	**ACC Toe-off post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**	**ACC Touchdown pre (SD)**	**ACC Touchdown post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**
CM distance m/body length	0.04 (4.76)	0.01 (−55.7)	HS60%	0.42 (0.03)	0.42 (0.04)	−0.01 (−1.56; 1.36)	$p = 1.00$, ES: −0.01	−0.04 (0.03)	−0.03 (0.03)	39.0 (−79.2; 157)	$p = 1.00$, ES: 0.39
			HS50%	0.43 (0.01)	0.43 (0.01)	0.16 (−1.22; 1.56)	$p = 1.00$, ES: 0.04	−0.04 (0.02)	−0.02 (0.03)	35.0 (−420; 490)	$p = 0.55$, ES: 0.70
			CON	0.43 (0.02)	0.44 (0.01)	1.04 (−0.82; 2.10)	$p = 1.00$, ES: 0.16	−0.03 (0.03)	−0.03 (0.02)	156 (−227; 540)	$p = 1.00$, ES: 0.00
CM angle (°)[a] Relative to horizontal	1.29 (2.75)	2.19 (2.36)	HS60%	46.8 (1.77)	47.4 (1.38)	1.32 (−0.59; 3.23)	$p = 1.00$, ES: 0.36	95.3 (4.19)	93.7 (3.37)	−1.63 (−3.02; −0.25)	$p = 1,00$, ES: −0.42
			HS50%	46.6 (1.22)	46.8 (1.08)	0.46 (−0.64; 1.57)	$p = 1.00$, ES: 0.17	95.2 (3.30)	92.6 (4.18)	−2.66 (−6.16; 0.82)	$p = 0.46$, ES: −0.69
			CON	47.7 (1.97)	47.5 (1.24)	0.45 (−0.81; 1.71)	$p = 1.00$, ES: 0.11	93.7 (4.99)	93.3 (3.13)	−0.32 (−2.36; 1.72)	$p = 1.00$, ES: −0.10
Hip-angle Ipsilateral (°) 180° = full EXT	6.31 (3.73)	10.7 (10.2)	HS60%	171 (7.61)	169 (6.72)	−1.19 (−3.07; 0.68)	$p = 0.72$, ES: −0.30	101 (7.30)	103 (5.28)	1.94 (−2.25; 6.14)	$p = 1.00$, ES: 0.26
			HS50%	174 (2.95)	175 (2.69)	0.12 (−1.59; 1.82)	$p = 1.00$, ES: 0.05	104 (8.10)	105 (6.14)	0.74 (−3.27; 4.75)	$p = 1.00$, ES: 0.07
			CON	170 (5.28)	171 (3.18)	0.41 (−0.51; 1.33)	$p = 1.00$, ES: 0.14	103 (8.73)	103 (5.95)	1.22 (−2.01; 4.44)	$p = 1.00$, ES: 0.12
Hip-angle Contralateral (°)[a] 180° = full EXT	5.97 (7.11)	9.12 (5.85)	HS60%	85.7 (6.72	82.8 (3.98)	−3.03 (−5.91; −0.15)	$p = 0.33$, ES: −0.51	161 (8.81)	154 (7.49)	−4.01 (−5.97; −2.05)	$p = 0.004^{**}$, ES: −0.80
			HS50%	86.7 (4.08)	85.6 (5.74)	−1.25 (−4.62; 2.10)	$p = 1.00$, ES: −0.22	164 (6.59)	162 (4.87)	−1.57 (−4.68; 1.56)	$p = 1.00$, ES: −0.48
			CON	85.1 (8.98)	84.6 (8.04)	−0.47 (−2.39; 1.46)	$p = 1.00$, ES: −0.06	159 (7.18)	155 (5.36)	−3.13 (−4.65; −1.61)	$p = 0.006^{**}$, ES: −0.80
Trunk angle (°) Relative to horizontal	4.97 (10.8)	6.62 (14.2)	HS60%	46.3 (5.20)	45.3 (3.03)	−1.48 (−6.44; 3.47)	$p = 1.00$, ES: −0.23	46.8 (6.18)	45.9 (2.59)	−0.73 (−7.25; 5.79)	$p = 1.00$, ES: −0.18
			HS50%	47.9 (2.87)	48.6 (3.77)	1.44 (−2.54; 5.41)	$p = 1.00$, ES: 0.20	49.1 (3.97)	48.8 (4.25)	−0.39 (−4.50; 4.21)	$p = 1.00$, ES: −0.07
			CON	46.5 (5.29)	46.6 (4.29)	0.59 (−2.10; 3.28)	$p = 1.00$, ES: 0.03	47.3 (5.50)	46.0 (4.24)	−2.26 (−6.25; 1.73)	$p = 1.00$, ES: −0.26

Spatiotemporal variables ACC	**MDC (%)**	**Group**	**Pre (SD)**	**Post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**
Contact time (s)	0.02 (9.32)	HS60%	0.19 (0.02)	0.18 (0.02)	−5.48 (−9.12; −1.83)	$p = 1.00$, ES: 0.56
		HS50%	0.19 (0.01)	0.19 (0.03)	−0.97 (−13.0; 11.01)	$p = 1.00$, ES: −0.12
		CON	0.19 (0.01)	0.18 (0.01)	−2.34 (−6.50; 1.82)	$p = 1.00$, ES: −0.34
Step Rate (Hz)	0.25 (5.71)	HS60%	4.19 (0.20)	4.32 (0.29)	3.25 (−0.56; 7.07)	$p = 1.00$, ES: 0.54
		HS50%	4.19 (0.17)	4.36 (0.41)	4.45 (−3.09; 12.0)	$p = 1.00$, ES: 0.56
		CON	4.27 (0.26)	4.28 (0.33)	0.54 (−2.61; 3.69)	$p = 1.00$, ES: 0.08

(*continued on next page*)

Table 4 *(continued)*

		Within-group statistics									
Kinematic variables ACC	**MDC (%) Toe-off**	**MDC (%) Touchdown**	**Group**	**ACC Toe-off pre (SD)**	**ACC Toe-off post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**	**ACC Touchdown pre (SD)**	**ACC Touchdown post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**
Step Length (m/body length)[a]	0.05(4.89)		HS60%	0.61 (0.06)	0.62 (0.06)	1.52 (−3.21; 6.24)	$p = 1.00$, ES: 0.13				
			HS50%	0.64 (0.03)	0.64 (0.04)	0.15 (−2.96; 3.26)	$p = 1.00$, ES: −0.50				
			CON	0.62 (0.05)	0.65 (0.05)	5.38 (1.12; 9.64)	$p = 0.23$, ES: 0.60				
Kinematic variables MAX	**MDC (%) Toe-off**	**MDC (%) Touch- down**	**Group**	**MAX Toe-off pre (SD)**	**MAX Toe-off post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**	**MAX Touchdown pre (SD)**	**MAX Touchdown post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**
CM distance to toe m/-body length	0.05 (8.27)	0.04 (−12.1)	HS60%	0.35 (0.01)	0.34 (0.01)	−2.09 (−3.76; −0.41)	$p = 1.00$, ES: −0.48	−0.23 (0.02)	−0.21 (0.02)	−5.84 (−10.9; −0.83)	$p = 0.63$, ES: 0.71
			HS50%	0.34 (0.02)	0.36 (0.03)	3.67 (−1.51; 8.85)	$p = 0.63$, ES: 0.44	−0.22 (0.02)	−0.21 (0.01)	−2.81 (−6.77; 1.16)	$p = 1.00$, ES: 0.44
			CON	0.33 (0.02)	0.33 (0.02)	−0.19 (−1.57; 1.19)	$p = 1.00$, ES:−0.02	−0.21 (0.02)	−0.21 (0.02)	−1.11 (−4.75; 2.53)	$p = 1.00$, ES: 0.09
CM angle (°)[a]	2.21 (3.87)	2.94 (2.64)	HS60%	56.6 (2.13)	57.1 (1.87)	0.95 (0.19; 1.71)	$p = 1.00$, ES: 0.26	114 (2.11)	112 (2.11)	−1.23 (−2.27; −0.20)	$p = 0.50$, ES: −0.67
			HS50%	57.6 (2.77)	56.1 (2.63)	−2.48 (0.19; 0.44)	$p = 0.55$, ES: −0.54	112 (1.64)	112 (2.01)	−0.44 (−1.16; 0.28)	$p = 1.00$, ES: −0.27
			CON	56.4 (2.38)	57.7 (2.17)	2.40 (0.77; 4.03)	$p = 0.32$, ES: 0.58	112 (2.37)	112 (2.49)	0.03 (−0.83; 0.90)	$p = 1.00$, ES: 0.01
Hip-angle Ipsilateral (°)	3.56 (1.77)	5.40 (4.03)	HS60%	201 (4.46)	201 (5.14)	0.13 (−0.99; 1.25)	$p = 1.00$, ES: 0.05	134 (6.15)	136 (5.40)	1.69 (−0.18; 3.56)	$p = 1.00$, ES: 0.38
			HS50%	202 (5.38)	202 (4.22)	−0.34 (−1.51; 0.82)	$p = 1.00$, ES: −0.15	141 (14.3)	140 (3.81)	−0.39 (−2.46; 1.67)	$p = 1.00$, ES: −0.04
			CON	202 (5.84)	201 (5.79)	−0.27 (−0.87; 0.32)	$p = 1.00$, ES: −0.10	135 (5.57)	136 (5.82)	0.41 (−1.51; 2.33)	$p = 1.00$, ES: 0.08
Hip-angle Contralateral (°)	3.92 (3.67)	6.17 (3.60)	HS60%	105 (3.42)	106 (4.94)	0.52 (−1.29; 2.33)	$p = 1.00$, ES: 0.13	176 (4.69)	173 (4.92)	−1.64 (−3.77; 0.49)	$p = 1.00$, ES: −0.61
			HS50%	107 (8.24)	104 (4.26)	−2.08 (−5.21; 1.04)	$p = 1.00$, ES: −0.39	174 (7.85)	172 (4.80)	−1.37 (−3.38; 0.64)	$p = 1.00$, ES: −0.39
			CON	106 (4.54)	107 (5.79)	1.13 (−1.17; 3.44)	$p = 1.00$, ES: 0.23	171 (11.6)	169 (13.2)	−1.40 (−3.44; 0.64)	$p = 1.00$, ES: −0.19
Trunk angle (°)[a]	2.14 (2.79)	2.40 (3.15)	HS60%	78.7 (4.37)	79.3 (4.36)	0.87 (−0.74; 2.51)	$p = 1.00$, ES: 0.15	79.9 (3.92)	80.4 (3.99)	0.61 (−1.66; 2.89)	$p = 1.00$, ES: 0.11
			HS50%	78.9 (5.48)	77.6 (3.48)	−1.48 (−4.23; 1.27)	$p = 1.00$, ES: -0.29	78.6 (4.43)	78.5 (3.86)	−0.09 (−2.22; 2.03)	$p = 1.00$, ES: −0.03
			CON	78.0 (5.54)	79.4 (3.73)	2.03 (−1.60; 5.68)	$p = 1.00$, ES: 0.28	77.9 (4.47)	79.0 (3.74)	1.52 (−0.96; 4.01)	$p = 1.00$, ES: 0.26

Spatiotemporal variables MAX	**MDC (%)**	**Group**	**Pre (SD)**	**Post (SD)**	**% Δ (95% CI)**	***P*-value (post-hoc), ES**
Contact time (s)	0.01 (10.9)	HS60%	0.13 (0.01)	0.12 (0.02)	−2.52 (−7.53 –2.48)	$p = 1.00$, ES: −0.32
		HS50%	0.12 (0.01)	0.12 (0.01)	−2.70 (−6.64 –1.23)	$p = 1.00$, ES: −0.51
		CON	0.12 (0.01)	0.12 (0.01)	0.56 (−2.47 –3.59)	$p = 1.00$, ES: 0.09
Step Rate (Hz)[a]	0.30 (6.60)	HS60%	4.30 (0.25)	4.48 (0.19)	4.38 (1.62 –7.14)	$p = 0.12$, ES: 0.82
		HS50%	4.47 (0.12)	4.65 (0.12)	4.00 (1.66 –6.33)	$p = 0.90$, ES: 1.50
		CON	4.50 (0.18)	4.53 (0.28)	0.67 (−2.82 –4.17)	$p = 1.00$, ES: 0.12
Step Length m/ body length	0.08(4.53)	HS60%	1.04 (0.04)	1.02 (0.03)	−1.39 (−3.07 –0.28)	$p = 1.00$, ES: −0.39
		HS50%	1.08 (0.06)	1.07 (0.07)	−1.37 (−3.75 –1.00)	$p = 1.00$, ES: −0.23
		CON	1.03 (0.08)	1.01 (0.06)	−1.38 (−5.26 –2.50)	$p = 1.00$, ES: −0.23

Notes.

HS, Heavy sled; CON, Control; TO, Toe-off; TD, Touchdown; CM, Center of Mass; m, meter; s, seconds; Hz, Hertz; ES, Effect size (Small: 0.2–0.59, Moderate: 0.60–1.19, Large 1.19 >); SD, Standard deviation; Δ, alpha (change pre post); NS, Nonsignificant.

[a] Significant main effect of time.

* Significant post-hoc difference pre- to post-intervention ($p < .05$).

** ($p < 0.01$).

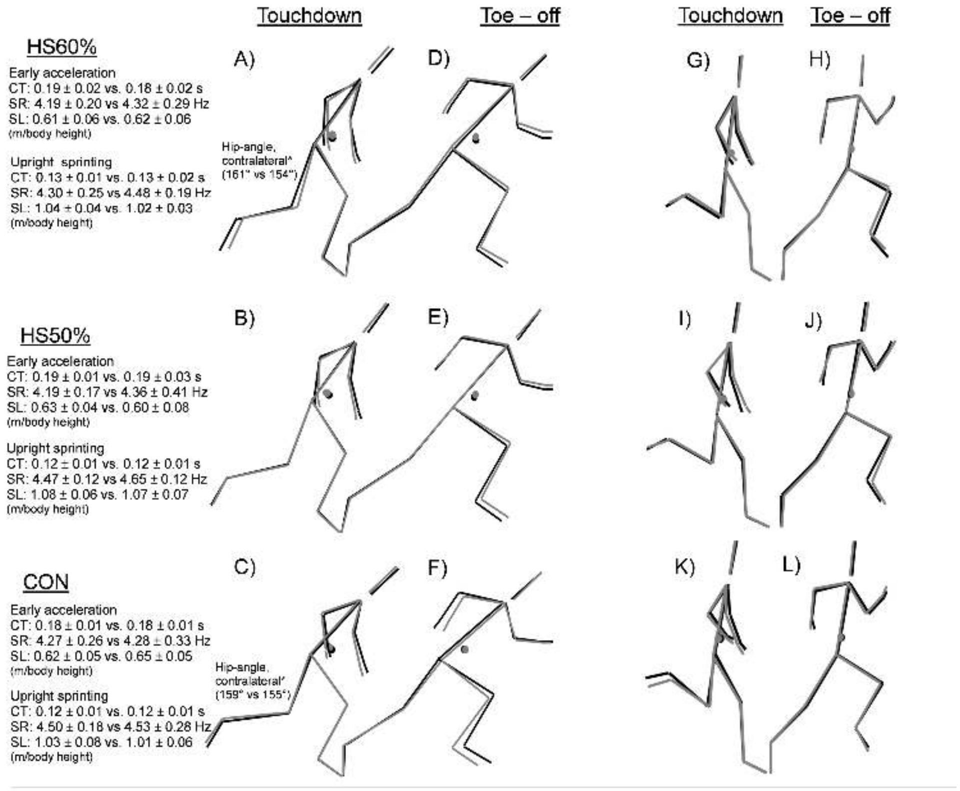

Figure 5 **Pre-post intervention sprint kinematic changes in early acceleration and upright sprinting.** Touchdown (A, B, C, J, I, K) and toe –off (D, E, F, H, J, L) within HS60%, HS50%, and CON groups. In early acceleration, toe-off is based on the average of the first push toe-off from the sprint start and the first two steps toe-off. The touchdown is based on the first 3 steps. Upright sprinting toe-off and touch-down are analyzed from 2 steps during upright sprinting at our close to maximal velocity (~22.5 m). No kinematic variables for within and between-group comparisons reached significance. HS: Heavy sled, CT: Contact time, SR: Step rate, SL: Step Length relative to body height, CM: Center of Mass. *: Significant within-group difference ($p < 0.05$).

Full-size DOI: 10.7717/peerj.10507/fig-5

(*Alcaraz, Elvira & Palao, 2014*; *Spinks et al., 2007*). However, moderate effect sizes were seen in some early acceleration kinematic parameters, including decreased touchdown CM distance and CM angle in HS50%, corresponding to potentially less time spent in the breaking phase due to contact times not changing. These changes make sense with our cross-sectional sled measurements (Fig. 4), as these were the two variables that showed the largest effect sizes for changes in movement. However, we found no relationships between changes in these variables and improvements in sprint performance, thus more accurate methodological approaches and/or larger sample sizes are likely needed for such short interventions. Furthermore, no negative effects of heavy resisted sprinting were observed on either early acceleration or upright sagittal plane sprint kinematics as speculated to some degree by previous literature (*Alcaraz et al., 2018*; *Alcaraz, Elvira & Palao, 2014*; *Alcaraz et al., 2008*; *Alcaraz et al., 2019*). While both HS60% and CON significantly decreased their contralateral hip angle at touchdown during early acceleration, this was likely due to normal fluctuations in sprint technique as the result remained under the minimal detectable change (HS60%: 3.13%, CON: 4.01%, MDC: 5.85%), rather than longitudinal alterations caused by the training protocols. One clear explanation is that potential deleterious effects were mitigated via coaching cues targeted to maintain good posture, in place of athletes adopting sub-optimal patterning during the heavy resisted sprinting. Our results cannot support the occurrence of longitudinal technical breakdown following heavy resisted sprint training, or at least indicate that such effects might be reduced with common-sense programming.

As an additional observation, our data showed that initial F*0* capacity and sprint FV-profile orientation seems to explain moderately adaptation potential (Fig. 4), corresponding to previous literature (*Lahti et al., 2020*). Thus, if an athlete already has a high force production capacity, or a force-oriented FV-relationship/profile, it should logically reduce adaptation potential to a high force –low velocity stimulus. This sample size does not allow for clear cut-off thresholds for training, however, a recent study using heavy resisted sprints in high-level rugby players showed nearly identical results. Therefore, an initial F*0* value around 8.4 $N.kg^{-1}$, or a sprint FV-profile lower than -0.95 will likely not respond well to heavy resisted sprint training (*Lahti et al., 2020*). Future studies should explore if varying from individualized (velocity decrement) heavy to light loads based on initial FV-qualities is of further value.

LIMITATIONS

The control group and the intervention groups were two different teams with inevitable differences in their training culture. Therefore, although initial sprint performance was highly homogenous, differences in training and recovery methods may have contributed to the results. This study also may have been underpowered for some variables, as based on the within- and between-group effect sizes, both groups showed similar trends in early acceleration, but only HS50% reached statistical significance. Furthermore, inclusion of a randomized control group that performs unloaded systematic acceleration training should be compared in future studies. The 2D motion analysis was only based on two time points, therefore caution is advised in their interpretation and future studies are implored to use more rigorous approaches. We did not have access to a high-resolution slow-motion camera, which likely contributed a couple of variables showing lower reliability. Similar to previous resisted sled training literature our sled study used a single time point method (toe-off, touchdown). A more ideal approach would likely be the analysis of waveforms, such as with the statistical parametric mapping method (*Schuermans et al., 2017*). We also acknowledge that the absolute reliability (ICC) confidence intervals can be considered large in numerous analysed variables, making it too imprecise to make accurate conclusions regarding their true reliability. Future studies using similar methods should include a larger sample size to improve reliability measurements.

CONCLUSION

Providing efficient evidence-based options to enhance sprint performance training is crucial for strength and conditioning coaches in high level soccer settings. It seems that in a time span of 11 weeks, one of the underlying reasons for heavy resisted sprint training improving sprint performance is increased force production (both directional and absolute). As this took place in a similar step time, the main driver seems to be improved mechanical power and likely rate of force development. Thus, our findings suggest that heavy resisted sprint training can improve sprint performance in professional soccer players. Adaptations may be potentially maximized with a 50% compared to a 60% velocity decrement resistance. A 50% velocity decrement resistance may provide a broader transfer across split-times, which should be verified in future studies. Based on the average amount of resisted sprints that were conducted during this study, the target should be to achieve at least 38 sprints divided over 2 months, preferably 1–2 per week, including a final taper. After familiarization, this stimulus can be integrated efficiently into field conditions, with a session duration lasting ~20 min for the entire team with 4+ sleds. Our results support the assertion that coaches do not have to worry about potential adverse effects on sprint technique if appropriate familiarization, cueing and supervision is used. Furthermore, coaches should be aware that heavy resisted sprint training will very likely not work for the entire team, which can be to some extent predicated by appropriate initial performance tests, including sprint FV-profiling.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Johan Lahti and Toni Huuhka conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Valentin Romero analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Ian Bezodis and Jean-Benoit Morin conceived and designed the experiments, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Keijo Häkkinen conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Human Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

The University of Jyvaskyla Ethical Committee granted ethical approval to carry out the study.

Data Deposition

The following information was supplied regarding data availability:

The raw data are available as a Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.10507#supplemental-information.

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4.3. ANALYSIS AND CONSIDERATIONS OF THEME II

Our main research question from study II that had relevance for this thesis was whether F*0* is trainable in a professional football setting. Improvements in F*0* were targeted via heavy resisted sprinting during the pre-season. The trainability of F*0* was of interest as previous literature has shown an initial association between lower levels of F*0* and increased HMI risk in football players (Edouard, Lahti, *et al.*, 2021), supported by study I results. Study II results demonstrated, as hypothesized, that trainability of F*0* depends on the players initial levels of F*0*, corresponding to previous literature in professional rugby (Johan Lahti, Jiménez-Reyes, *et al.*, 2020). In other words, the fastest accelerators in this cohort were non-responders. Although the 50% VL (Velocity-Loss) resisted sprint load was the only load to induce improved sprint performance on a group level compared to the control group (10-m time, $p < 0.05$, ES = 1.03), both 50 % and 60 % VL groups showed similar improvement trends for F*0* (60 % VL, ES =1.00 vs. 50 % VL, ES = 1.04). In Figure 25, we demonstrate that F*0* individual adaptation data from both the current study and Lahti, Jiménez-Reyes, *et al.*, (2020) where very heavy resisted sprint training (75 % VL) was used in professional rugby players. A highly interesting result was that the linear relationship between initial levels of F*0* and improvements in F*0* were markedly similar, with F*0* x-intercept values being at 8.2 N.kg^{-1} in the rugby cohort vs. 8.5 – 8.6 N.kg^{-1} in the football cohort. When analyzing the entire group, the intercept is at 8.4 N.kg^{-1} (Figure 25, B).

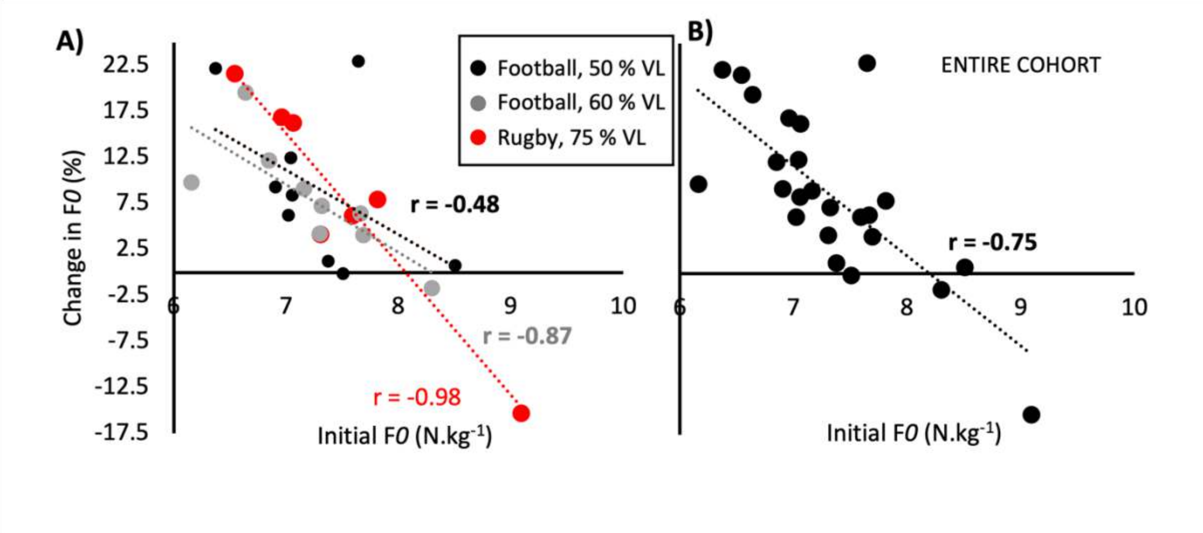


Figure 25. Correlations between initial values of F*0* and changes in F*0* post short-term heavy resisted sprint training in professional team-sports. A) Separate correlations of different heavy loads in three different heavy resisted loads in football and rugby B) Summarized correlation of all data from both studies. Data taken with permission from Lahti, Huuhka, *et al.*, (2020) and Lahti, Jiménez-Reyes, *et al.*, (2020). VL: Velocity loss.

The similarity in results likely strengthens the universality of the results within sprint-based team-sport settings. Therefore, it seems that players with an F*0* above 8.4 $N.kg^{-1}$ are unlikely to respond to resisted sprinting of the magnitudes used in this study as the main modality to improve F*0.* The degree of adaptation will likely also depend to some degree on the maximal velocity capabilities of the players in relation to their maximal force capabilities (i.e., their sprint FV-profile) (Morin and Samozino, 2016; Lahti, Jiménez-Reyes, *et al.*, 2020). Furthermore, the pre-intervention between-session minimal detectable change (MDC) % was used as a novel approach to help verify true change in the intervention groups, which was 9.53 % for F*0* (all reliability measurements can be found in Appendix 2, Tables 2.3 - 3.10). From a strict point of view, interpreting the results based on the 9.53 % minimal detectable change threshold means that the intervention was sufficient to improve beyond a doubt only 6/18 players F*0* (i.e., their improvements were over 9.53 %). The six players that improved over the minimal detectable change threshold had an average F*0* of 6.78 $N.kg^{-1}$ (range: 6.16 – 7.64 $N.kg^{-1}$). Such levels of F*0* can be considered as low to moderate considering the levels found in study I among 7 professional teams. The lack of responders past 9.53 % could be due to the lower resisted sprint volume per session compared to previous literature (Cahill *et al.* 2019). However, if the volume would have been much higher, it may have risked fatiguing the players before football practice. Another possible reason is that the intervention was not long enough considering the small dose per-session. This likely is one valid reason as demonstrated by our additional measurements (not published in study II). In Figure 26, we present the intervention groups additional measurements of F*0* during the season. This includes a mid-measurement (between pre and post) and a mid-season measurement (nine weeks after post-testing). After post-testing, the team reported that they aimed to maintain the results through the season via at least one session per week.

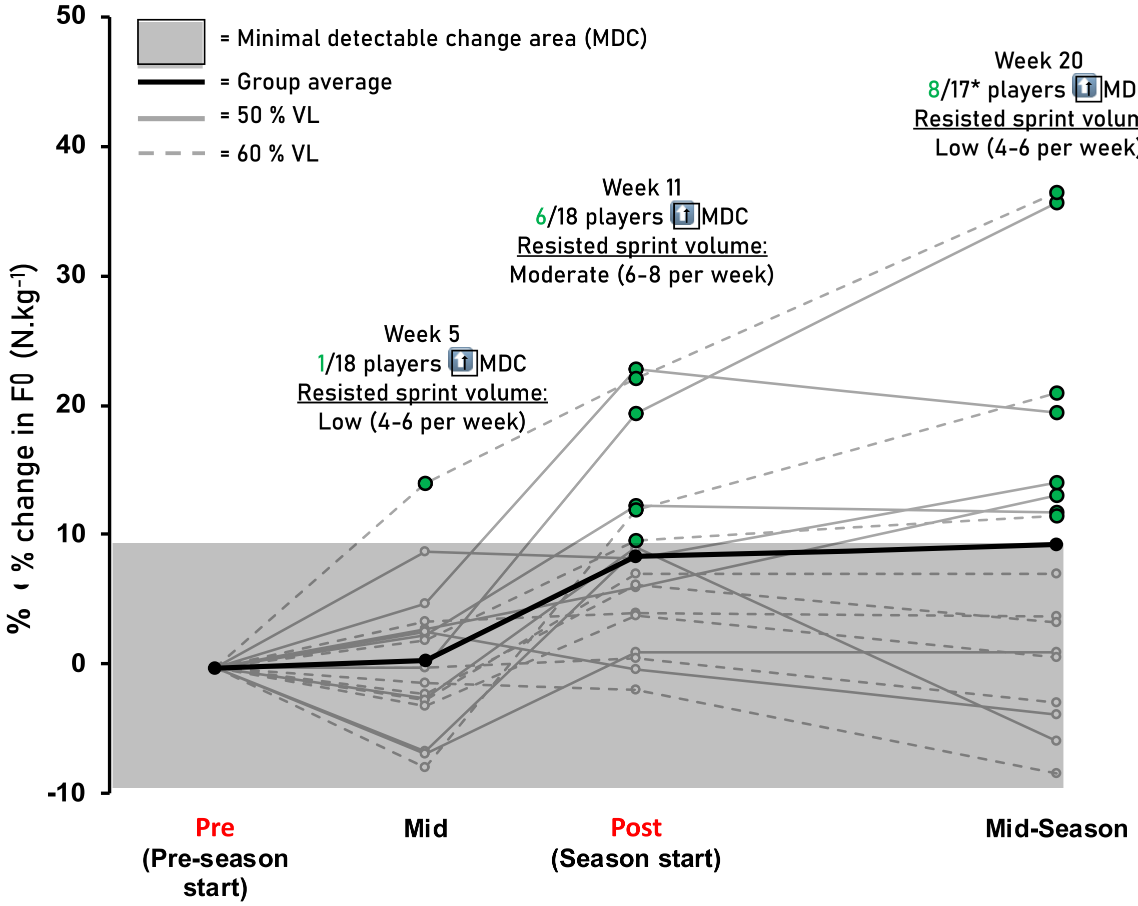


Figure 26. Additional measurements of F*0* in the intervention groups during the football season. The additional measurements titles are colored in red. The zone between pre and post is the intervention period. The gray box represents the MDC zone. The black line is the entire cohorts average. The gray line is the 50 % VL group and the dashed gray line the 60 % VL group. VL: Velocity loss. F0: Maximal theoretical horizontal force. *: Mid-season measurement included 17/18 players, the player that was not available had an F*0* improvement of 9.06 % at the post-measurements (60 % VL group).

As demonstrated in Figure 26, two additional players moved past the minimal detectable threshold when mid-season measurements were included (their initial F*0* was within the range of the other responders; 7.02 – 7.05 N.kg^{-1}). No visible differences between resisted loads are emphasized when including this additional data. It should be mentioned that the minimal detectable change found in the study II cohort was higher compared to previous literature (Lahti, Jiménez-Reyes, *et al.*, 2020). This could be also due to the smaller sample and that only two sprints were used to interpret performance. However, as F*0* likely depends on multiple neural and structural properties within and between the working muscles, numerous training intervention components are warranted for broader trainability (Morin and Samozino, 2016; Bellinger et al., 2021). Despite this, an important aim of study II was to explore the feasibility of adding one potential training option into a busy football microcycle, in this case heavy resisted sprint training. The results show that such training can be successfully implemented in a real-world setting, with potentially slightly broader transfer with a 50 % VL load vs. the 60 % VL load. Furthermore, this was done without negatively influencing long-term unresisted sprint kinematics as speculated by previous literature (Alcaraz, Elvira and Palao, 2014; Alcaraz *et al.*, 2018, 2019). More studies are still needed to confirm whether similar linear relationships and measurement errors are found.

The sample size of Study II was too small for testing the causal link between increasing players F*0* and reducing HMI risk. Hence the focus was on sprint performance. However, there were some potentially relevant observations from the two cohorts for future HMI studies. There was a total of four HMI within the two teams during the season: one within the intervention team and three within the control team. The intervention teams HMI tally of 1 was also the lowest among the seven teams in study I. All injuries took place within three months of testing. Three of the injured players (two from the control team and one from the intervention team) had their pre-season F*0* over one standard deviation lower than the league average. The seven teams average was 7.63 ± 0.60 $N.kg^{-1}$, whereas one player had 6.94 $N.kg^{-1}$ (control team), the second 6.79 $N.kg^{-1}$ (control team), and the third 6.76 $N.kg^{-1}$ (intervention team). In Figure 27, the intervention teams changes in F0 are shown on an individual level with the injured player highlighted in red.

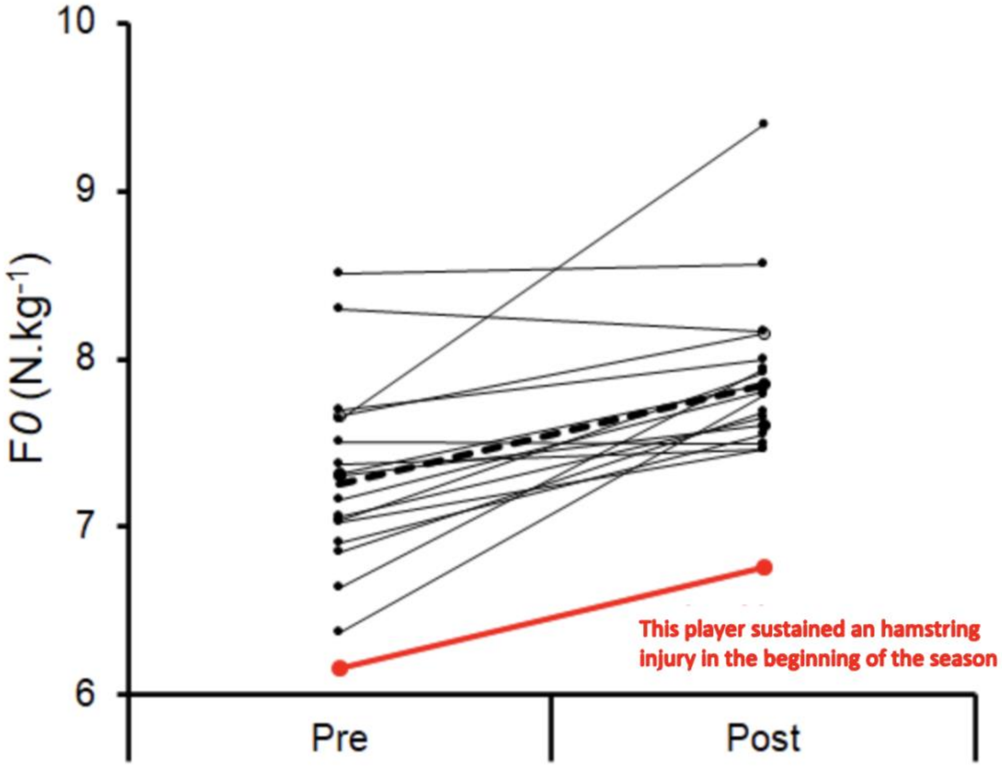


Figure 27. Pre-post F*0* *levels* in the intervention teams players. Test were done in the beginning of pre-season and in the end of pre-season The dashed line represents the team average, and the red line represents the only player sustaining a hamstring injury during the season.

The fourth player who sustained a HMI (control team) had a F*0* slightly above the league average; 7.72 $N.kg^{-1}$. At the end of the study, the intervention team had a 2 % higher average F*0* compared to the league average from study I (7.76 $N.kg^{-1}$ vs 7.63 $N.kg^{-1}$). As mentioned, after the post-testing they reported to maintain resisted sprint training at least once per week during the season. During mid-season tests the intervention team had a 3 % higher average F*0* compared to the rest of the teams (8.02 $N.kg^{-1}$ vs 7.79 $N.kg^{-1}$). As the causes behind HMI are multifactorial (Ayala *et al.*, 2019; Green *et al.*, 2020), any variable in isolation (such as F*0*) will inevitably contain overlap between injured and non-injured players (van Dyk, Farooq, *et al.*, 2018). However, it seemed that at least one fundamental difference in the intervention team compared to the more injury-prone control team was the inclusion of non-specific sprint training during the entire season. In this case heavy resisted sprint training (combined with short sprints). Furthermore, the lack of changes in kinematics from heavy resisted sprinting may also be a relevant result for risk reduction purposes. This is because one speculated change induced by heavy resistance included increased trunk flexion (Alcaraz *et al.*, 2018), which has been shown to increase hamstring MTU strain (Higashihara, Nagano and Takahashi, 2017). As reported, no such effects were seen with the reported coaching methods, or any other change that may increase hamstring length.

To conclude, study II's results support the use of heavy resisted sprinting to assist increases F*0* in professional football settings, especially in individuals with lower F*0* (~7.00 N.kg^{-1}). The above-mentioned observations from study II (combined with study I results) support the evidence-guided decision to further explore whether there is relevance in increasing football players F*0* to reduce the risk of HMI within a multifactorial program, potentially assisted with heavy resisted sprinting.

5. THEME III, MULTIFACTORIAL AND INDIVIDUALIZED TRAINING FOR HMI RISK REDUCTION

5.1. RESPONDING TO THE THIRD AND FOURTH RESEARCH QUESTIONS

After epidemiological evaluation and identification of possible risk factors for HMI, the final stage of the TIP model includes to intervene (O'Brien *et al.*, 2019). Can the incidence of hamstring injuries in professional football be reduced by introducing new intrinsic intervention measures? As most professional football teams arguably have ongoing hamstring injury risk reduction training strategies, the question is whether the approach can be further improved with help of a training intervention. A training intervention is ideally done through a gold standard RCT study design. However, as discussed, randomization in "real-life" professional cohorts is highly challenging. As teams have already to different extents active multifactorial or even individualized protocols, agreeing to an RCT would have required some teams to risk downgrading their protocols. This would have been a high financial risk for the clubs and thus not plausible. In such cases, prospective cohort studies are considered a valid compromise (Arnason *et al.*, 2008; Suarez-Arrones *et al.*, 2021). This is where two seasons or more are compared in a non-randomized manner where potential seasonal differences are controlled for. Essentially, such a study explores prospectively whether a specific change or changes in ongoing risk reduction training approaches from one season to the next leads to a substantial change in injury risk. If multiple changes are made to ongoing training protocols, one cannot identify what exact changes in ongoing training protocols helped more than others (Suarez-Arrones *et al.*, 2021). Therefore, such study format rather assists in exploring whether a specific training programming approach may be more successful compared to what was used during the control season.

Updating risk reduction approaches includes multiple layers of challenges, including improving testing frequency and design, training quality and adherence to training (Suarez-Arrones *et al.*, 2021; van der Horst *et al.*, 2021). Recently, Bahr, Thorborg, and Ekstrand (2015) showed that despite the existence of compelling evidence, Champions League and Norwegian Premier League teams did not systematically adopt the NHE as an injury risk reduction exercise. Consequently, injury-risk reduction programs that have shown to be effective in trials do not necessarily reduce injuries in a real-world setting (Finch, 2006). Beliefs among the coaching staff and players need to be clearly addressed with education (van der Horst *et al.*, 2021). However, motivation for adherence may also be improved when risk reduction approaches avoid monotony (i.e., boredom) and when they are more connected with performance outcomes (Møller *et al.*, 2021; Suarez-Arrones *et al.*, 2021). Therefore, it is likely important to have a screening and training design that is also performance based. Individualization of programs may further reduce the risk of monotony and improve motivation as they are fundamentally connected to feedback, especially if its frequent (Jackson *et al.*, 1998; Chatzisarantis and Hagger, 2007). Thus, the final questions of the thesis were created:

3) *Can a feasible multifactorial training system be created that individualizes hamstring risk reduction programs in a professional football setting?*

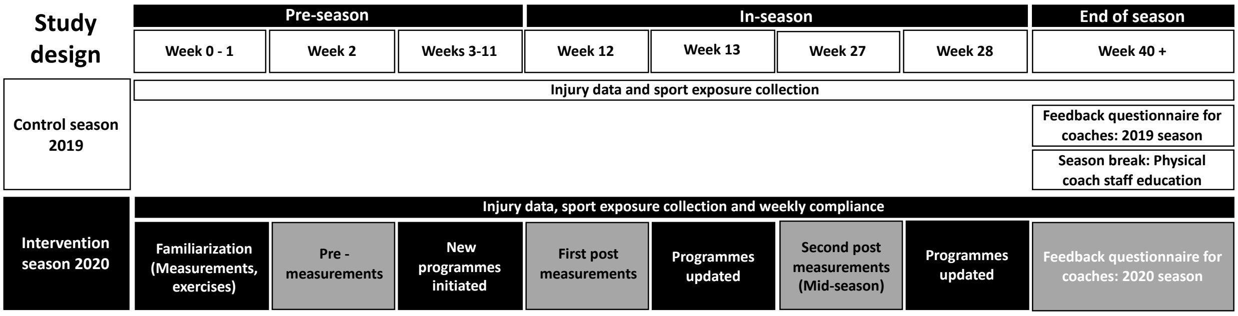
4) *Can hamstring muscle injuries be further reduced in a professional football setting by introducing a multifactorial and individualized training approach?*

Two questions led to two aims being established, both forming separate studies, which were:

1) Introducing the framework of innovative multifactorial and individualized HMI risk reduction program designed to further reduce HMI in professional football.

2) Conducting a prospective cohort intervention within professional football teams to see whether HMI can be reduced from one season to another.

The general design of the prospective cohort intervention study is provided in Figure 28. The aim was to collect injury and exposure data from both the control season and intervention season and additionally training compliance data from the intervention season. Before the intervention season, and extensive educational workshop was provided to the physical coaches and physiotherapists as they would be responsible for conducting the training. Seasonal differences would be compared statistically with cox-regression hazard ratios.



Study design	Pre-season			In-season				End of season
	Week 0 - 1	Week 2	Weeks 3-11	Week 12	Week 13	Week 27	Week 28	Week 40 +
Control season 2019	Injury data and sport exposure collection							
								Feedback questionnaire for coaches: 2019 season Season break: Physical coach staff education
Intervention season 2020	Injury data, sport exposure collection and weekly compliance							
	Familiarization (Measurements, exercises)	Pre - measurements	New programmes initiated	First post measurements	Programmes updated	Second post measurements (Mid-season)	Programmes updated	Feedback questionnaire for coaches: 2020 season

Figure 28. Intervention study timeline.

Individualization requires some form of test criteria that classify on an individual level. Hence, we used the test results from the screening protocol presented in study I to do so. As the screening protocol itself is multifactorial, responding to all tests by making changes to the program in each category automatically leads to training that is both multifactorial and individualized. Therefore, lumbo-pelvic control, range of motion, posterior chain strength, and sprint mechanical output were all used as categories for testing, which led to changes in training on an individual level in each category (Figure 29).

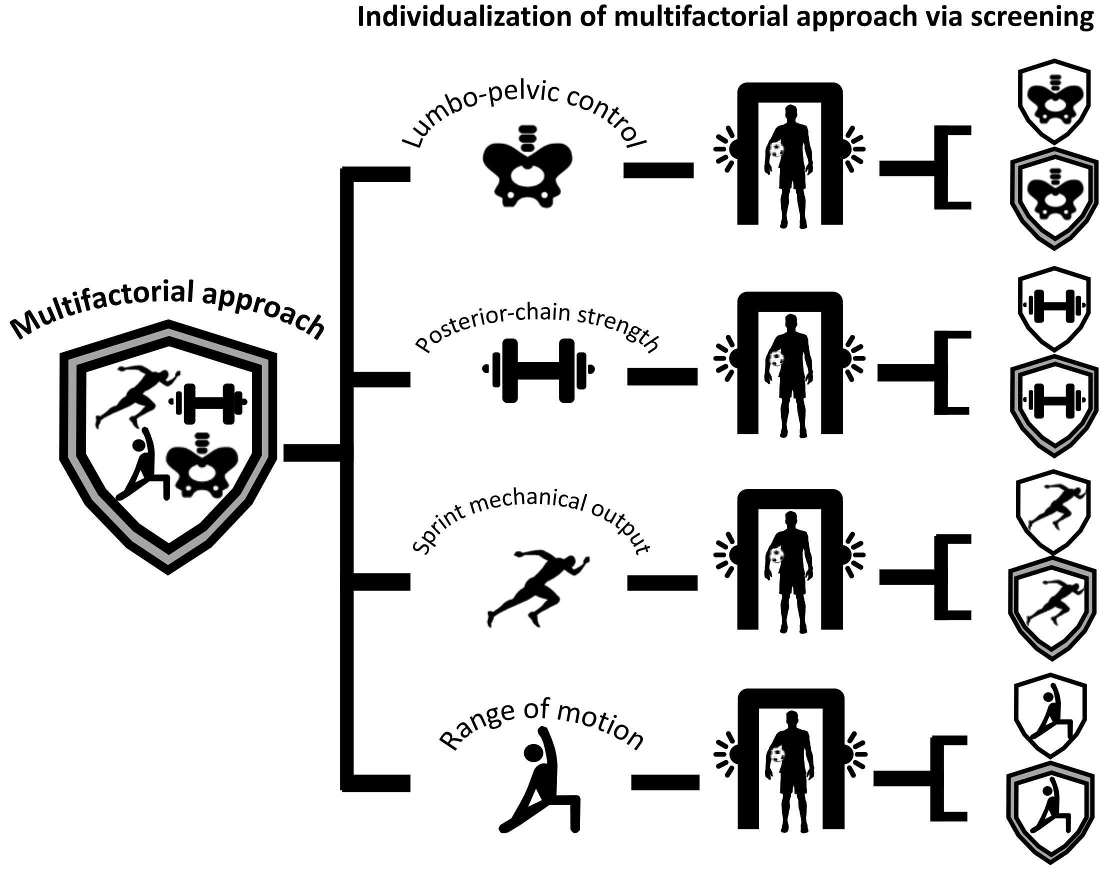


Figure 29. Basic structure of the multifactorial and individualized approach. Players are screened in four categories so that they can be given individual training programs.

Despite the unclear risk association results from study I, the screening protocol was considered to have clinical relevance for evolving hamstring risk reduction training approaches in many professional football cohorts (such as the Finnish premier league). The difficulty of controlling for the complexity of football in risk assessment studies (such as study I) has been acknowledged in literature (Bahr, 2016; Bittencourt *et al.*, 2016; Ruddy *et al.*, 2019). For example, despite one meta-analysis showing that the inclusion of NHE training showing up to 51 % reductions in HMI among thousands of football players (Van Dyk, Behan and Whiteley, 2019), it has also shown to be of low utility in predicting injury risk (Van Dyk *et al.*, 2017). Therefore, until complex multivariable prediction models become more feasible in club settings (Ayala *et al.*, 2019), decisions for intervention structures lean equally on evidence guided decisions and anecdotal experiences. Based on numerous visits and discussions within the Finnish league, there was a lack of systematic and/or high-quality multifactorial training for HMI risk reduction. Furthermore, individualization was mostly only conducted in rehabilitation settings. This also meant that teams in varying degrees could have all the training categories in use from the screening protocol (i.e., multifactorial training), but they were potentially not conducted optimally (e.g., unsystematic, lack of progressions, or exercises that are not biomechanically sound). This training behavior defines what was done during the control season, which is good for transparency to report in basic detail. Therefore, we decided to conduct a questionnaire for the physical training coaching staff both before and after the intervention that aimed to assist interpretation in what truly changed by conducting the intervention. This questionnaire would be published alongside the intervention results (Appendix 3, Tables 3.3).

An important distinction is that the individualized layer builds upon a multifactorial base. The players initial priority is to train with quality in a multifactorial manner for HMI risk reduction (Mendiguchia, Alentorn-Geli and Brughelli, 2012; Ayala *et al.*, 2019; Buckthorpe *et al.*, 2019). This is the safest approach as the chosen tests for individualization have not been assessed for specificity (i.e., capacity and accuracy to detect true negatives). This means that it was not considered safe to have specific players completely passive in one of the multifactorial training categories due to their negative test result. Furthermore, for players that were considered to have good test results, maintenance training was considered essential as the demands from the sport could lead to reductions in performance (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020). Some teams in study I that reported not training systematically within specific training categories on a regular basis also in general showed moderate to large reductions in those categories during the season. Therefore, systematic high-quality multifactorial training was considered the most important training aim for all involved players.

Individualization can be done in multiple ways, such as manipulating exercises, training volume, and training progressions based on specific screening results (Jiménez-Reyes *et al.*, 2016; Mendiguchia *et al.*, 2017). However, not much literature exists on the topic as most intervention studies focus on group changes. To make the approach more feasible in numerous club settings, we decided to use a percentile method to individualize players within each team. This meant that within each of the four training categories, players were ranked as either positive or negative based on a predetermined percentile threshold. The positive or negative result based on the percentile determined mostly the volume of training in each category. This meant that players that were ranked as positive in a specific category were considered to need a higher training weekly volume, and the players with negative scores only requiring maintenance training. The only expectation to changes in training volume was the sprint mechanical output category, that instead individualized the load of the resisted sprinting (Figure 30).

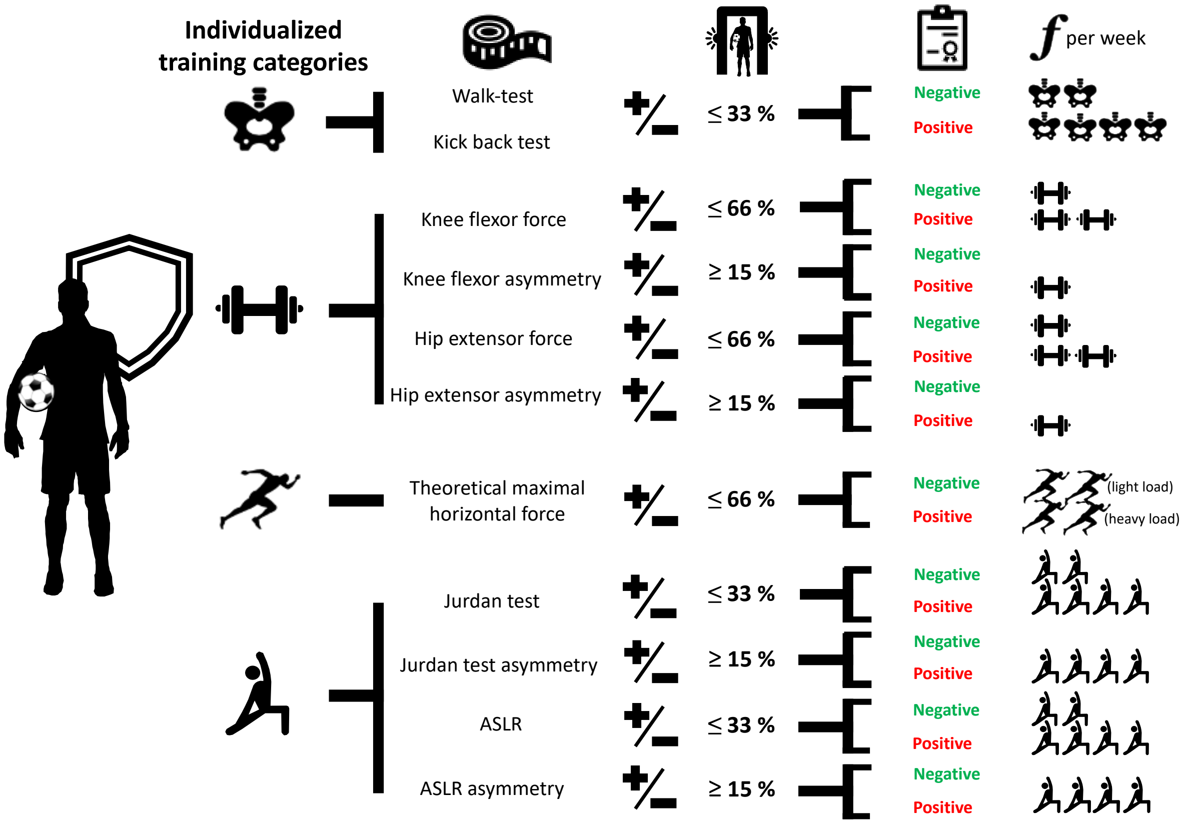


Figure 30. Individualized training program structure based on test results. Percentile criteria for negative or positive scores are placed on a total of 11 tests. All results influence what the training week looks like for the players. ASLR: Active straight leg raise.

Below are the thresholds for each category and their corresponding changes in training visualized in Figure 30:

1) *Lumbopelvic control.* Screening included two tests: the Walk-test and the Kick-back test. If players had a percentile rank of ≤ 33 % in their team in either test, they were considered to have a positive test result. A positive test resulted in a lumbo-pelvic training target of x 4 per week, whereas a negative test result (≥ 34 %) resulted in a training target of x 2 per week.

2) *Posterior chain strength.* Screening included four tests: knee flexor force output, hip extensor force output, and between-limb asymmetries in both tests. In terms of strength levels, knee flexor and hip extensor strength were considered as separate training focuses. If a player had a percentile rank of ≤ 66% in their team, they were considered to have a positive result. A positive test resulted in a training volume of x 2 per week in either knee flexor or hip exenstor strength or both (i.e., positive result in both tests). A negative test result (≥ 67 %) led to a training volume of x 1 per week. An asymmetry of ≥ 15 % led to an extra set of strength training for the weaker leg x 1 per week.

3) *Range of motion.* Screening included two tests: the ASLR test and the Jurdan test. If players had a percentile rank of ≤ 33 % in their team in either test, they were considered to have a positive test result. A positive test resulted in a lumbo-pelvic training target of x 4 per week, whereas a negative test result (≥ 34 %) resulted in a training target of x 2 per week.

4) *Sprint mechanical output.* Screening included one test: theoretical maximal horizontal force (F*0*) via sprint force-velocity profiling. If players had a percentile rank of ≤ 66 % in their team in either test, they were considered to have a positive test result. A positive test (i.e., low F*0*) resulted in training with higher resisted sprinting loads x 2 per week, whereas a negative test result (≥ 67 %) resulted in a training with lighter resisted sprint loads x 2 per week.

The higher percentile in the posterior strength training category was chosen because it included higher scientific validity based on current literature (i.e., more evidence to show its likely positive influence) (Green *et al.*, 2020; Pizzari, Green and van Dyk, 2020). In the sprint mechanical output category, where improvements in F*0* were the main target, learnings from study II were used for program design. Resisted sprint training was proposed as the main modality to improve F*0*, with either heavy or light loads. Based on the larger cohort data from study I, it was considered likely that each team would include players with a high F*0* (i.e., clearly above 8 $N.kg^{-1}$). As players with high F*0* may not respond to heavy loads (Lahti, Huuhka, *et al.*, 2020; Lahti, Jiménez-Reyes, *et al.*, 2020), we hypothesized that they may respond to the opposite, i.e. light loads. The criteria for either heavier or lighter resisted sprint training loads was based on the learnings from study II and previous literature (Lahti, Jiménez-Reyes, *et al.*, 2020). Range of motion and lumbo-pelvic control included the exception of two tests that aimed to assess the same thing (i.e., if the player needed more training in range of motion or lumbo-pelvic control). This was done simply because both categories included a novel test (the Kick-back test for lumbo-pelvic control, and the Jurdan test in the range of motion category). Therefore, it was considered safer to have a reinforcing test. The 15 % threshold of asymmetries in range of motion and posterior chain strength was based on previous asymmetry focused literature and our pilot reliability data (JCroisier *et al.*, 2008; Lahti *et al.*, 2021), showing that under 15 % differences may be due to measurement error.

Programming and periodization options were discussed in detail during the education workshop among the team physical coaches. This discussion went both ways (i.e., between the scientists and practitioners), as there is a low amount of research exploring what training stimulus should be placed where in the microcycle for optimal results in a professional football context (Cross *et al.*, 2019). The initial training volume prescription was advised as being the ideal scenario for one-match weeks. For congested two-match weeks, the target was to maintain results, thus reducing the target training volume roughly by 50 %. However, it was advised to get in as many low-load sessions as possible (i.e., range of motion and lumbopelvic control), as they can be considered highly flexible because they are likely less fatiguing. These were placed as only guidelines as match weeks can fluctuate highly in structure.

The frequency and the timing of testing were important to consider. Previous literature supports the premise that performance can fluctuate substantially during the season (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020). Therefore, screening has been advised to be conducted frequently during the season (van Dyk, Bahr, *et al.*, 2018; van Dyk, Farooq, *et al.*, 2018). As one of the thesis targets was to prove "feasibility” of the hamstring screening protocol, it was important to provide a proof of concept by conducting the protocol more than once during the season. Thus, the target was placed for three rounds of screening tests: one during the beginning of the pre-season, the second at the start of the season, and the third around mid-season. This meant that individual programs would be given three times during the season.

As presented in study I, clinical tests were targeted to be performed 72 hours post-match and sprint testing 96 h post-match (Ispirlidis *et al.*, 2008; Matinlauri *et al.*, 2019). All screening tests were conducted by an experienced practitioner from the research team, although teams were also educated to complete the tests if needed.

Due to time and different facility constraints, we could not individualize each training component of interest. For example, monitoring maximal velocity exposure has been shown to be an important component to consider for hamstring risk reduction (Duhig *et al.*, 2016; Malone, Roe, Doran, Gabbett Collins, 2017; Colby *et al.*, 2018; Malone, Owen, *et al.*, 2018).

One possible way of individualizing such an approach would be to use GPS data on a weekly basis and determine which players need less or more maximal velocity exposure. However, not all teams in our cohort had GPS systems systematically in use for all players (i.e., not enough units). Furthermore, we hypothesized based on discussions with coaches that the problem was more the lack of maximal velocity exposure and not the other way around. Therefore, we decided to create an additional non-individualized training category called “training for all players“ (i.e., same structure for all players), which included high-speed sprinting and sprint drills. Additionally, three other components were considered important to include in the “training for all players” category: post-sport ROM, triceps surae health, and manual therapy (Figure 31).

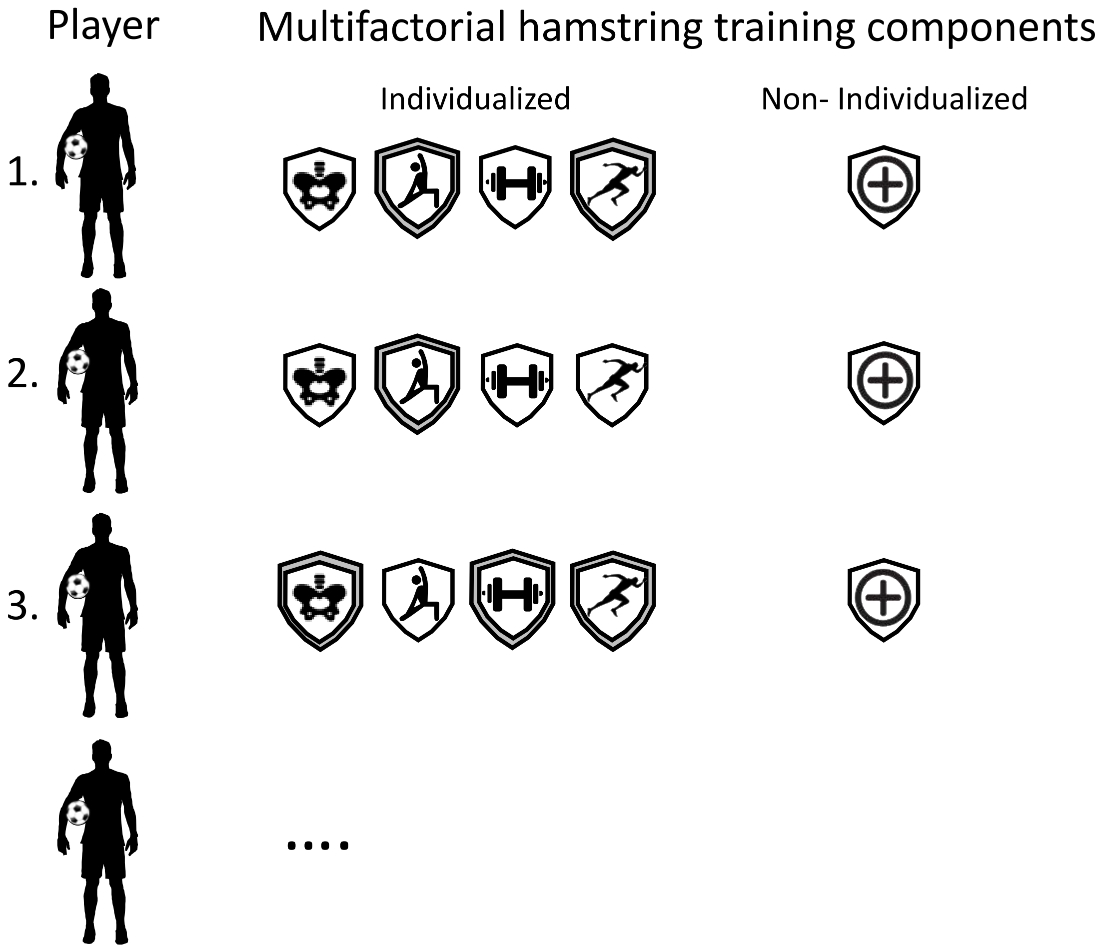


Figure 31. Additional inclusion of a non-individualized training category called ”training for all players” to the intervention.

Post-sport ROM (i.e., range of motion training conducted after football training) and manual therapy aimed at countering the potential increase in stiffness that can be observed from football exposure (Satkunskiene *et al.*, 2020). This included ’relaxing’ the muscle-tendon units of the hamstring muscles and other muscle groups that influence the length of the hamstring muscles. This was done with the help of the team manual therapist/physiotherapist and, if needed, using foam-rolling. These muscle groups that were considered of primary importance were iliopsoas, rectus femoris, latissimus dorsi, adductor magnus, and erector spinae (Chumanov, Heiderscheit and Thelen, 2007; Takaki *et al.*, 2016; Mendiguchia, Gonzalez De la Flor, *et al.*, 2020). The triceps surae health focuses on strengthening the triceps surae complex, which can be also considered a part of the posterior chain musculature. The relevance of training the triceps surae area is supported by recent evidence showing that ankle injuries may increase the likelihood of sustaining and index HMI (Malliaropoulos *et al.*, 2018). Furthermore, the gastrocnemius muscle has been shown to have a small contribution in decelerating the knee during the late swing phase (Schache *et al.*, 2012), therefore possibly assisting the hamstring muscles. Thus, the target was to strength train the triceps surae complex twice per week.

All exercises in the entire protocol used to target specific categories were planned to be filmed and published with the main findings. All exercises were based on up-to-date evidence on targeted parameters. This included common exercises for the hamstrings such as NHE, sliders, hip thrust, the Romanian deadlift, and dynamic stretches (Bourne *et al.*, 2017; Hegyi, Csala, *et al.*, 2019; Iwata *et al.*, 2019; Brazil *et al.*, 2021), but also less common evidence-based exercises such as "tantrum" kicks, sprint drills, lumbo-pelvic control exercises, resisted sprinting, and curved-sprinting (Janusevicius *et al.*, 2017; Fílter *et al.*, 2020; Lahti, Huuhka, *et al.*, 2020; Mendiguchia, Conceição, *et al.*, 2020; Mendiguchia, Gonzalez De la Flor, *et al.*, 2020).

Finally, compliance is considered one of the hardest challenges when introducing new approaches (Nassis *et al.*, 2019; van der Horst *et al.*, 2021). One key to compliance is considered the importance of educating the coaching staff to extensively understand a new approach (Suarez-Arrones *et al.*, 2021). In turn, this may help the coaches motivate the players more. Therefore, our aim was to provide an extensive education workshop for all coaches before the intervention season. Monitoring compliance in each category was planned for the entire season. This would help both answer to what extent specific categories were trained and to what extent they were individualized. In turn, a more comprehensive discussion can be achieved in interpreting the results. Furthermore, the availability of this data could potentially allow for interesting association calculations between training frequency and changes in variable results.

5.2. MULTIFACTORIAL INDIVIDUALISED PROGRAMME OR HAMASTRING MUSCLE INJURY RISK REDUCTION IN PROFESSIONAL FOOTBALL: PROTOCOL FOR A PROSPECTIVE COHRT STUDY

BMJ Open Sport & Exercise Medicine

Multifactorial individualised programme for hamstring muscle injury risk reduction in professional football: protocol for a prospective cohort study

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ABSTRACT

Introduction Hamstring muscle injuries (HMI) continue to plague professional football. Several scientific publications have encouraged a multifactorial approach; however, no multifactorial HMI risk reduction studies have been conducted in professional football. Furthermore, individualisation of HMI management programmes has only been researched in a rehabilitation setting. Therefore, this study aims to determine if a *specific* multifactorial and individualised programme can reduce HMI occurrence in professional football.

Methods and analysis We conducted a prospective cohort study over two seasons within the Finnish Premier League and compare the amount of HMI sustained during a control season to an intervention season. Injury data and sport exposure were collected during the two seasons (2019–2020), and a multifactorial and individualised HMI risk reduction programme will be implemented during intervention season (2020). After a hamstring screening protocol is completed, individual training will be defined for each player within several categories: lumbo-pelvic control, range of motion, posterior chain strength, sprint mechanical output and an additional non-individualised 'training for all players' category. Screening and respective updates to training programmes were conducted three times during the season. The outcome will be to compare if there is a significant effect of the intervention on the HMI occurrence using Cox regression analysis.

Ethics and dissemination Approval for the injury and sport exposure data collection was obtained by the Saint-Etienne University Hospital Ethics Committee (request number: IORG0007394; record number IRBN322016/CHUSTE). Approval for the intervention season was obtained from the Central Finland healthcare District (request and record number: U6/2019).

INTRODUCTION

In professional football, hamstring muscle injuries (HMI) account for 20–26% of all sustained injuries,[1 2] making them one of the most prevalent. Furthermore, nearly one-third of HMI have been reported to recur.[3] HMI has been considered a long-lasting, unresolved problem within football[4]; according to some research, HMI have increased.[5] Due to lost playing and training time, HMI is considered being one of the largest burdens in professional football, including diminished performance and financial loss.[2 5] Therefore, there is a need to continue improving HMI risk reduction strategies.

HMI are most often sustained during sprinting, but also commonly via slide tackling (overstretch), cutting (change of direction) and kicking.[1] Multiple intrinsic risk factors have been established with large variation in importance, some of which are unmodifiable, including age, gender, ethnicity and injury history.[4 6] Possible modifiable intrinsic risk factors include the strength of the hamstring and surrounding lumbo-pelvic muscles, strength asymmetry, fatigue tolerance, muscle architecture, range of motion (ROM), lack or excess of high-speed sprinting and sprint performance technique.[4 7] Therefore, by present-day standards, the underlying optimal strategy to manage HMI is generally agreed to be multifactorial.[4 7 8] Furthermore, these training strategies should be contextualised to the general demands of the sport and changes within practice. Practitioners and scientists contest the extent to which each intrinsic risk factor can be modified and how each of them should be trained.[4 7–10] Multiple intervention programmes within football have aimed to reduce the risk of HMI by unifactorial means, with both the largest focus and success given to isolating improvements in eccentric knee flexor strength.[11–13] However, to the best of our knowledge, no multifactorial injury reduction studies have been conducted in professional football settings where the demands are arguably the highest.

Additionally, there are no unifactorial or multifactorial HMI risk reduction studies using high-speed sprinting as a training method. This is despite evidence showing that the potential lack of optimal sprinting kinematics,[14 15] a lack of exposure to maximal velocity sprinting[16] and even lower sprint performance[17] are risk factors associated with lower body and HMI in sprint-based team sports. The inclusion of sprint work is further made compelling by the fact that sprint performance capability is considered one of the key performance tests distinguishing lower- and higher-level football athletes.[18 19] The muscle activity of the hamstrings in sprinting surpasses common hamstring strengthening exercises,[20] which supports their use as a time-efficient means of training for performance and injury risk reduction simultaneously. This in return could foster cooperation between team physiotherapists and strength and conditioning coaches, which might help create a multidisciplinary practical approach for reducing the risk of HMI.

Although a general multifactorial injury risk reduction approach is likely needed, professional football players vary substantially in how many risk factors they possess.[3] Therefore, from a holistic injury management perspective, a multifactorial approach should be individualised.[4 7 21] Specifically, individualisation is an approach where training towards a certain common outcome, such as reducing injury occurrence (eg, injury risk reduction programmes), is constructed to a certain extent independently for every player. This is done by first evaluating what training stimuli a certain individual seems to require based on categories of 'screening' tests. Research within football using individualised training for HMI risk reduction has only been completed once,[22] whereas research including individualised multifactorial training has only been performed within a hamstring rehabilitation setting.[21] Individualisation can also be done by merely manipulating the training volume of a certain stimuli or even within exercise selection depending on the situation.[23]

Therefore, this study aims to determine if a *specific* multifactorial and individualised programme can reduce the occurrence of HMI in a professional football setting.

METHODS AND ANALYSIS

Study design and procedure

We conducted a prospective cohort study over two professional football seasons. The 2019 season serves as the control season, including sport exposure and injury data collection. The 2020 season serves as the intervention season, including the implementation of a multifactorial and individualised HMI risk reduction programme in addition to the sport exposure and injury data measurements obtained, as per the control season. The study design is presented in figure 1.

Participants

The participants were recruited from teams within 'Veikkausliiga', the professional football premier league in Finland. For each team, the recruitment will be done by separately contacting each team's strength and conditioning coach and physiotherapist. The teams within the league without a full-time strength and conditioning coach and a physiotherapist are included in the present study. Thereafter, the objectives, procedure and risks of the study are explained orally and in written format by the leading author (JL) to the staff and players. Strong contact networks have already been established with all the participating teams due to an ongoing collaborative research projects within the same league. Subsequently, players were included or excluded based on the criteria presented in table 1.

Written consent for the study will be sent via email at least 1 week prior to initial testing, and participants must have signed consent. Players under 18 require parental approval. Participation is entirely voluntary, and they may refuse any test or exercise at any time and for any reason. Participation, suspension or exclusion will in no way affect the position of those recruited for research in their team community.

Patient and public involvement

Many of the researchers (JL, JM, LA, TK, MK, AM, VP, MT and R-MT) involved in the present study have worked and continue to work in clinical practice dealing with injured football players. As they have shared their stories underpinning injury occurrence, these football players

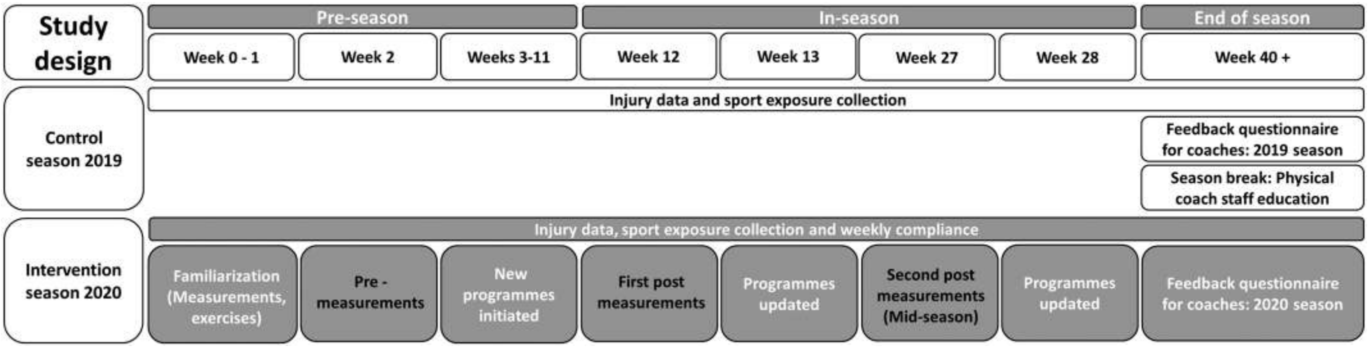


Figure 1 Study design. The study includes one control season (2019) and one intervention season (2020) with a total of three measurements.

Table 1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criterion
▶ The player accepts that their medical data can be collected ▶ The players are involved in training sessions through the start of the 2019 and 2020 preseason (January) to end of the season (October).	▶ Goalkeepers (only field players included due to a higher hamstring injury risk).

indirectly assisted in the hypothesis-making process for the current study. No football players were, however, invited to take active part in the design of the current study via, for example, knowledge-transfer scheme.

Primary outcome: HMI

Injury definition and data collection

Injury is defined as traumatic or overuse physical damage that occurred during a scheduled training session or match that caused absence from the next training session or match.[24] Injury data are prospectively collected and registered by each team's physiotherapist, using a standardised report form including the date of injury, circumstances (match/training), injury location, type, cause and date of return to play.

Hamstring muscle injury definition

The primary outcome of the present study will be the occurrence of HMI. HMI is defined as an injury, located at the posterior side of the thigh, and involving muscle tissue. Hamstring injuries defined as cramping/spasm are also included as muscle injuries. The diagnosis will be made by interview and physical examination of the players and confirmed by ultrasound or MRI.

Other data collection

Anthropomorphological measurements and player information

The players' body mass (in kg), height (in cm), age (in years) and player position are registered at the start of each of the two seasons. Further, the moment arm distances are measured at the knee and hip during manual dynamometry strength testing so that strength can be reported in torque format.

Sport exposure definition and data collection

Sport exposure is defined as weekly training hours and matches within each team's season. This data will be collected by either the team strength and conditioning coach or physiotherapist.

Physical coach staff education

After measurements, full responsibility will be given to each team's physiotherapist and strength and conditioning staff to instruct and monitor the completion of the training programme. To ensure high standards, video material and a weekend workshop were organised for all strength and conditioning coaches, physiotherapists and other practitioners responsible for injury risk reduction within the team.

All staff participating in the educational workshop and subsequent data collections complete two questionnaires at different time points during the study to improve the qualitative interpretation of results (online supplemental tables 8 and 9). The first questionnaire, completed at end of the 2019 season but before the educational workshop, aims to clarify understanding of current HMI risk reduction practices within the team. The second questionnaire, completed before the end of the intervention season, aims to determine what training categories and methods of the intervention the participating staff consider to be the most impactful on their practice compared to the control season. It includes their opinion on the compliance of the players. Furthermore, the lead author (JL) of the study will be fully available for questions during the entire study.

Intervention: multifactorial and individualised HMI risk reduction programme for professional football

Each player's HMI injury risk reduction *training protocol* will be largely based on the results of the multifactorial hamstring *screening protocol* results, which determines individualised training targets. The implementation of the entire injury risk reduction training protocol will be managed by the team's strength and conditioning coach and physiotherapist after being fully educated at the end of the control season.

Overview of the hamstring screening protocol for football (Football Hamstring Screening)

The intervention season includes three sessions of screening tests over the ~42-week season (figure 1). For each team, all screening tests were performed within a 2-day period and completed once at the start of pre-season (PRE), once at the end of the pre-season or start of the season (POST1) and a final test mid-season (POST2). Due to different scheduling of team practices, teams were screened within 3 weeks of each other.

The Football Hamstring Screening (FHS) protocol will be divided into the following categories that we considered important for football players: lumbo-pelvic control, ROM, strength and sprint mechanical output (figure 2). All clinical tests included in the lumbo-pelvic control, ROM and strength assessment total of 20 min per player. The sprint mechanical output test, which will be combined with sprint kinematic 'kick-back' analysis for the lumbo-pelvic control screening category, lasts 3–5 min per athlete or 10–15 min for the entire team. To improve reliability, all tests within each team were performed by the same experienced clinician (JL) with a mandatory familiarisation for all clinical screening tests 1 week pre-testing. Appropriate initial steps are taken to help transfer the screening protocol into practice. Reliability testing has been conducted (manuscript in revision) in combination with a prospective cohort study to help support the FHS protocols validation in accordance with Bahr *et al*.[25]

Efforts are made to standardise the order and timing in which teams and players are screened and the given exposure time to the training intervention before post screenings are initiated. The FHS protocol is divided into clinical tests and sprint tests, both of which are tested before practice and/or on a rest day. To control for fatigue, players completed clinical testing a minimum of 72 hours post matches,[26] whereas sprint testing will be completed a minimum of 96 hours post matches.[27]

This research project will be specifically designed so that both the screening and training protocols can be efficiently integrated into the athletes' training environment. This will be possible as the teams already have reserved time slots for their own frequent testing and physical training protocols, and the changes made by the research protocol were made in their own training environment and support the general aims of their practice.

Lumbo-pelvic control tests

Lumbo-pelvic control will be tested via one clinical test and one sprint kinematics test done in parallel with sprint mechanical output testing. The first lumbo-pelvic control test, that is a part of the clinical tests, is named the 'walk test', which uses a validated WIVA digital gyroscope (Let-Sense Group, Castel Maggiore, Italy) to estimate 3D pelvic kinematics in walking.[28] It has greater intrasubject and intersubject repeatability for pelvic kinematics measurements compared with stereo optoelectronic systems.[29] To further improve reliability, we use a composite score of the sagittal and frontal plane pelvic movement in normal gait. The test includes the player walking 10 m forward and back twice with the WIVA digital gyroscope attached to the S1/L5 junction.

The second lumbo-pelvic control test will be included in the 30 m maximal sprint performance test, which assessed simple sagittal plane 2D upright sprinting kinematics using a high-speed camera (240 fps) at the 22.5 m mark, 11 m perpendicular to the line of sprinting. This test aims to indirectly assess suboptimal sagittal plane lumbo-pelvic movement in sprinting by focusing on the lower-limb angles at touchdown and toe-off (figure 3). Excess rotational work being completed by the lower limbs 'behind the body' (centre of

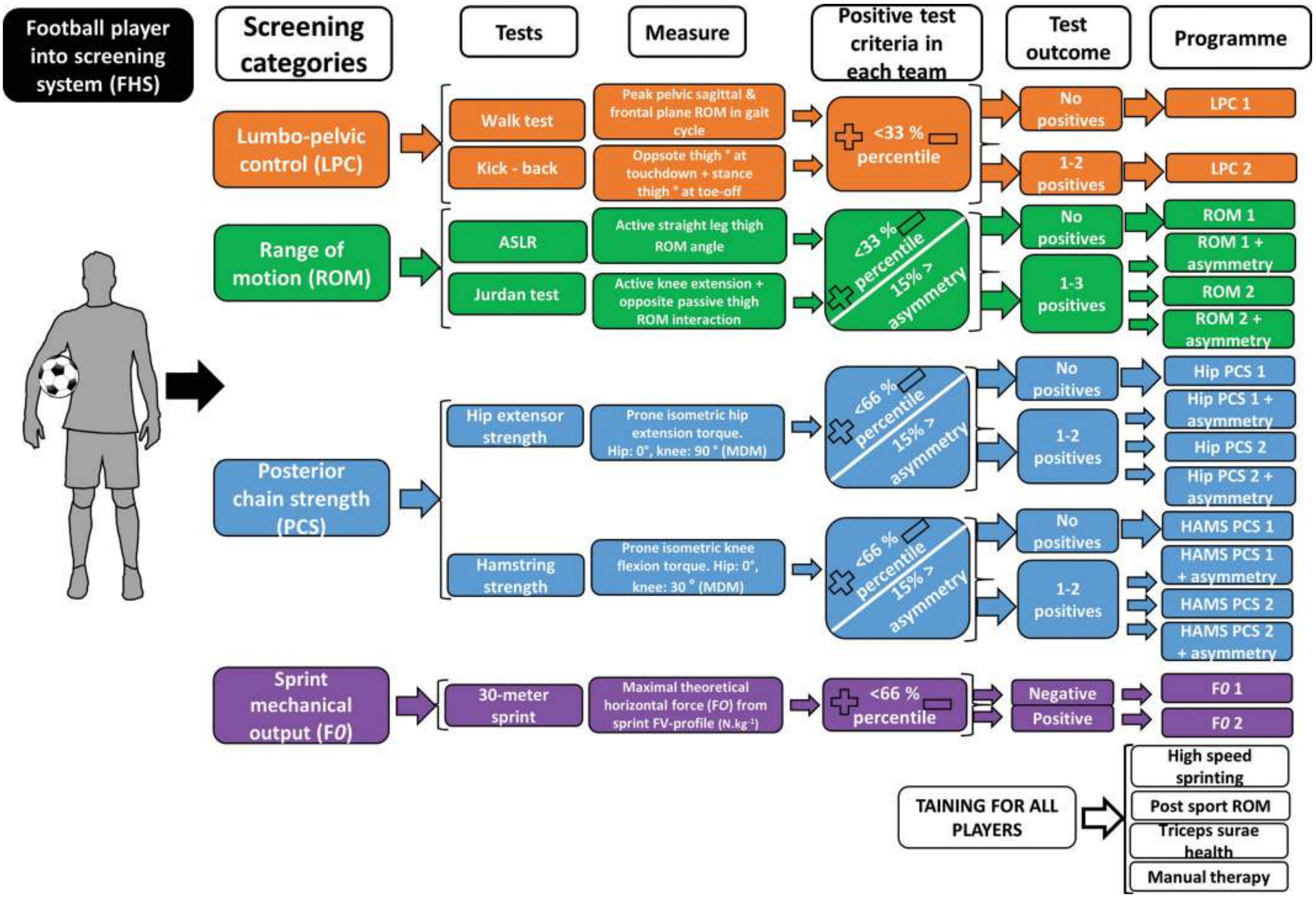


Figure 2 Hamstring screening protocol and training programme selection. Initially, the football player is tested within four screening categories. A percentile method within each team is used in all categories to define whether a player's test outcome is positive or negative. Further, asymmetry is measured in the ROM and strength screening categories, adding further detail to the programmes. ASLR, Active Straight Leg Raise; FHS, Football Hamstring Screening; MDM, manual dynamometer.

mass) is associated with the 'kick-back' mechanism and is a sprint coach concept related to the quality of 'front-side mechanics'.[30] Angles are calculated based on the mean value of two strides (touchdown and toe-off) within two maximal sprints using Kinovea video analysis software (v.0.8.15), and an example of the calculation method is provided in figure 3.

ROM tests

The FHS protocol includes two ROM tests: Active Straight Leg Raise (ASLR) and a new proposed test named the 'Jurdan test' (figure 4C and D). After one familiarisation repetition, tests are performed twice at a slow pace (3 s), and angles averaged for improved reliability using a validated digital goniometer app (Goniometer Records, Indian Orthopedic Research Group).[31]

The ASLR test has been shown to be a high reliability active hamstring flexibility test, where the thigh angle is measured from a controlled straight leg lift in supine position.[32] The Jurdan test is new to the literature and is derived from anecdotal observations by experienced health professionals to be an interesting option for further scientific scrutiny. The aim of the test is to demonstrate the interaction between hip flexor and hamstring flexibility, which has been considered a potential risk factor in sprinting.[33] The Jurdan test position and execution is considered to be a combination of the modified Thomas test[34] and the active knee extension test.[32] Initially, the participant is supine in a similar position to the modified Thomas test but is asked to complete an active knee extension (holding the thigh at 90°) while holding the table and holding the lumbar spine in contact with the table. The lumbar position will be verified kinaesthetically by the practitioner in the starting position and visually during execution. Maintenance of the thigh angle at around 90° for the active knee extension during testing is visually verified. The result will be defined as the difference between the actively lengthened legs shin angle and the opposite legs passive thigh angle (which is hanging over the table's edge). Both angles are measured relative to horizontal. From figure 4C and D, this corresponds to the following calculation: 53°—(−16°)=69°, where 53° is the shin angle and −16° is the opposite leg's negative thigh angle. Another example result that leads to the same value, but different ROM values would be 72°–(3°)=69°, where 72° is the shin angle and 3° is the opposite leg's positive thigh angle. Therefore, this composite angle does not focus on which specific leg's ROM is potentially the most problematic but instead focuses more on the leg interaction. This also corresponds to the approach behind the selected risk reduction ROM exercises in the training programme.

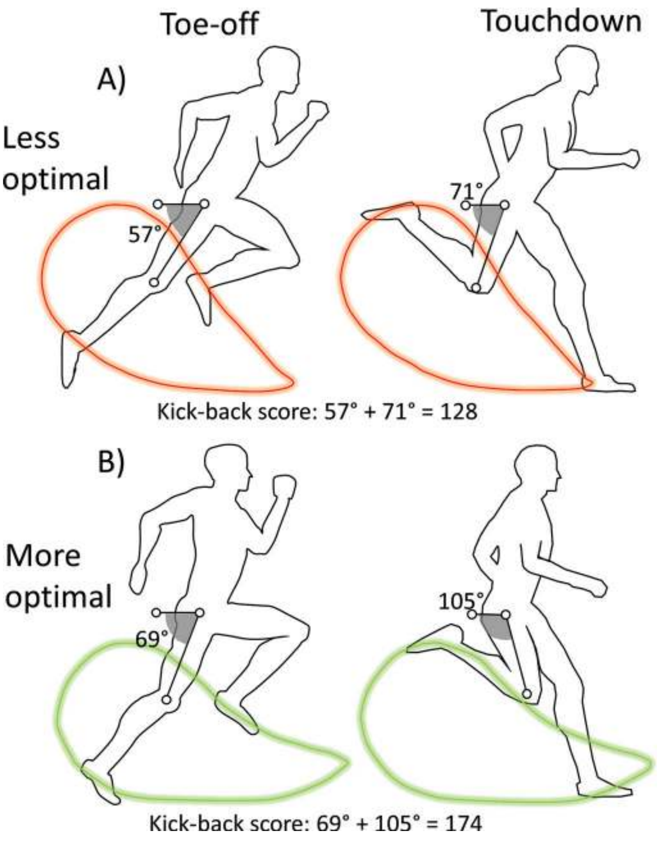


Figure 3 The 'kick-back' mechanism is quantified by composite angle score within the sprint stride; the contralateral thigh angle at touchdown and the ipsilateral thigh angle at toe-off. Angles were placed after first manually digitizing of the hip, and knee joint centres. Less (A) or more optimal (B) is based on both anecdotal evidence from practitioners and Schuermans *et al*[14] results (see figure 4 for a similar visual). The less or more optimal movement is also visualised with tracking the foots path through the sprint stride cycle. Within each team, football players' kick-back mechanism will be classified as positive if they are ranked at or under the team's percentile of 33%, corresponding to increased lumbo-pelvic training.

Posterior chain strength tests

Isometric strength for hip extensors and knee flexors will be assessed using a handheld dynamometry method in previously described reliable positions.[35 36] Participants laid in a prone position on a table while strapped from the waist (figure 5). The knee flexors are tested in 0° of hip extension and 30° of knee flexion with force placed on the heel. The knee flexion angle start position will be verified by the digital goniometer. As no apparatus will be used to hold the knee flexion position during contraction, shielding during contraction is expected to be around 5°. The hip extensors are tested in a 0-degree position with the knee extended to 95–100° with force placed on the distal tibia. The dynamometer will be placed at ~5 cm from knee flexion crease,[33] which determines how far the shin needs to be pushed backed so that the calf muscle is not in the way. A belt will be placed across the hips to avoid raising of the gluteals during the test.

Sprint mechanical output test

Players perform two 30 m maximal sprints in sequence with football practice. Specifically, sprints are performed

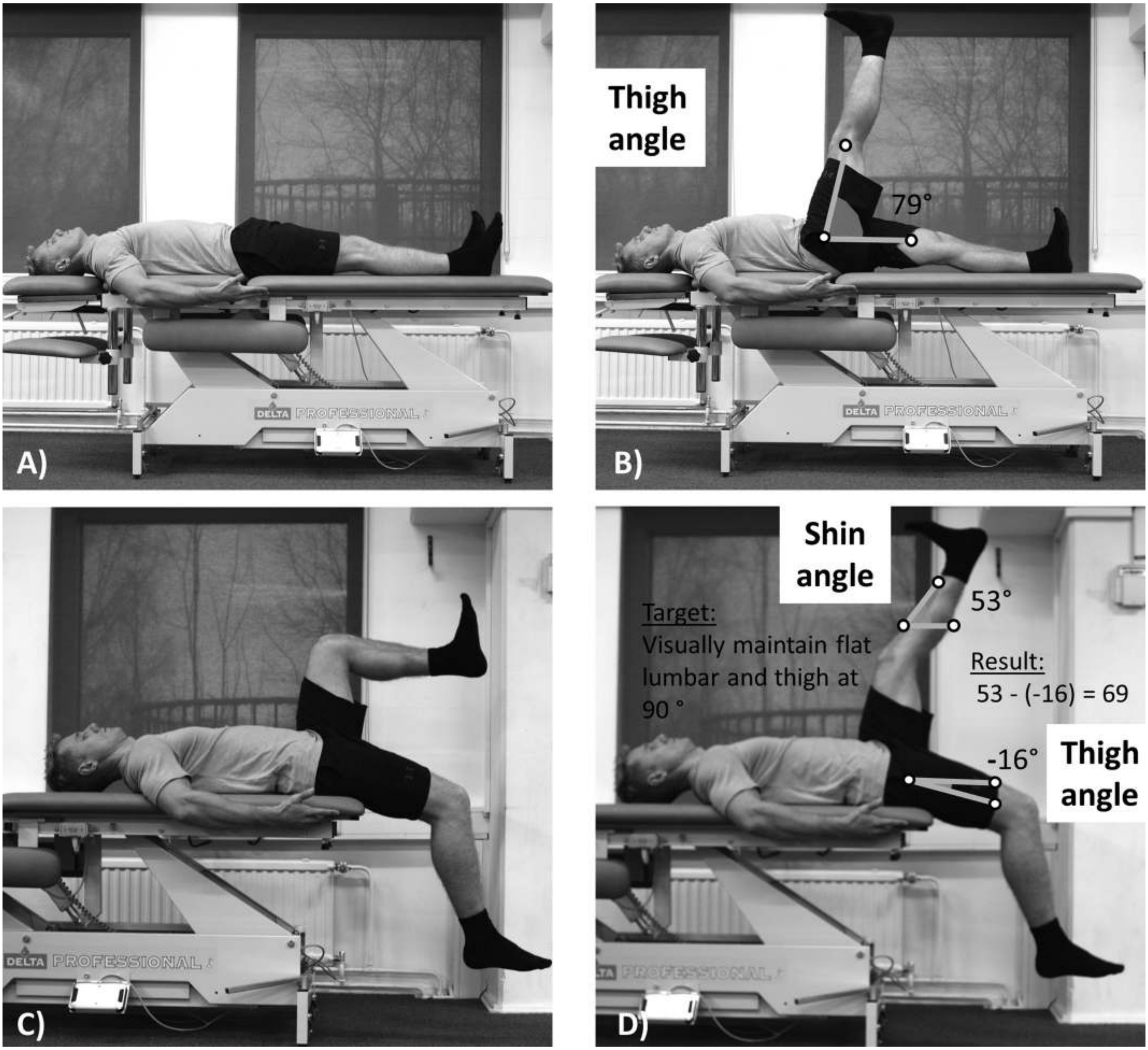


Figure 4 Range of motion tests used in the study. Picture (A) and (B) are from the Active Straight Leg Raise test (ASLR) and pictures (C) and (D) from the 'Jurdan test'. Within each team, football players' range of motion will be classified as positive if they are ranked at or under the team's percentile of 33% in any of the range of motion tests, corresponding to increased range of motion training. If asymmetry is found between legs (≥15%), increased range of motion training will be prescribed for the less flexible leg.

after the team's normal sprint testing warm-up protocol and with 3 min of passive recovery between sprints. Sprint performance (split times 0–5, 0–10, 0–20 and 0–30 m), maximal velocity and sprint mechanical output (ie, maximal theoretical horizontal force (F0)) are computed using a validated field method measured with a radar device (Stalker ATS Pro II, Applied Concepts, TX, USA) as reported previously.[37–39] Briefly, this computation method for F0 is based on a macroscopic inverse dynamic's analysis of the centre-of-mass motion. Raw velocity–time data wereare fitted by an exponential function. Instantaneous velocity data are then be combined with system mass (body mass) and aerodynamic friction to compute the net horizontal antero-posterior ground reaction force.[39] Individual linear sprint force–velocity profiles are then extrapolated to calculate relative F0.

Individualised HMI risk reduction protocol

Training within the HMI risk reduction protocol will be completed in the exact same categories as used within the FHS protocol: lumbo-pelvic control (table 2), ROM (table 3), posterior chain strength (table 4) and sprint

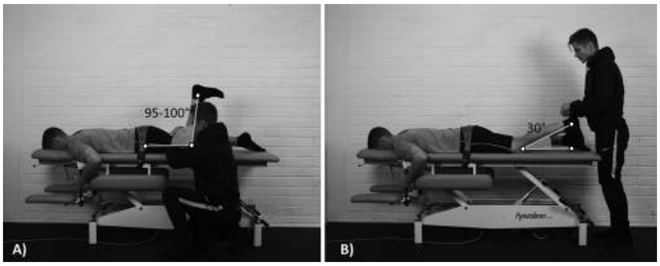


Figure 5 Posterior chain strength tests. The hip extensors are tested in position (A) and knee flexors in position (B). Within each team, football players' knee flexor strength and hip extensor strength are separately classified as positive if they are ranked at or under the team's percentile of 66%, corresponding to increased strength training for the respective joint. If asymmetry is found between legs at any joint (≥15%), increased training is prescribed for the weaker leg.

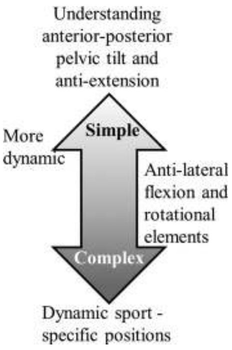
mechanical output (table 5). In every screening test category, football players are either ranked as positive or negative within each team and then accordingly given individual training protocols that are instructed by each team's coaching staff (figures 2 and 6). The approach for determining positive and negative cut-offs is explained in more detail in the following section. Each individualised training protocol includes the same exercises for all players, but the training volume varied based on the individual. In practical terms, if a weakness is found (ie, 'positive' result), the player should work on the weakness more. However, due to the physical requirements in football, even those with negative test scores complete maintenance training within each category; therefore, all players benefit from at least minimal lumbo-pelvic, posterior chain strength, ROM and sprint mechanical output training.

Cut-offs used for individualisation of the HMI risk reduction protocol

Individual training protocols are designed largely based on a percentile cut-offs within each team in all four screening categories. These percentiles are based on both evidence-based guidelines and consistent anecdotal evidence from experienced practitioners within professional football in the research team. Current evidence suggests that strength training has the highest validity in injury risk reduction.[10] This is why the posterior chain strength category includes the highest cut-off percentile to classify positive or negative players compared to the other categories. This means that there is a higher likelihood that a player will be ranked as positive in the posterior strength training category compared to ROM and lumbo-pelvic control, leading to an increased training volume. Specifically, the higher percentile of 66% has been chosen for posterior chain strength, whereas ROM and lumbo-pelvic control have a lower cut-off percentile of 33% (figure 6).

In practical terms, based on the screening scores in the lumbo-pelvic and ROM categories, a positive result (percentile ≤33%) corresponds to a target training volume of four times per week and a negative result (percentile >33%) corresponds to a target volume of twice per week. If there is more than one positive in a specific testing category, it has

Table 2 Lumbo-pelvic control

Structure of exercises within both A and B sessions	Exercise category	Weekly session volume (2–4 sessions)	Exercises	Sets and reps
	A	Negative test results: once per week (A) Positive test results: twice per week (A+A)	1. Stir the pot 2. Plank to bridge 3. Hip hinge 4. Anti-side flexion split squat jumps 5. Overhead A-skips	2×6 rotations per side 2×3 s holds per position 2×8 2×8 2×6–8 skips per side
	B	Negative test results: once per week (B) Positive test results: twice per week (B+ B)	1. Dead bug scissor kicks 2. Side plank roll to dead bug 3. Rotations with bar 4. Hip hinge into wall kick 5. Lateral overhead step-ups	2×8 kicks per side 2×3 s per position 2×5 m (forward and backward) 2×4 per side 2×4–6 per side

Programming design for lumbo-pelvic control. There are two categories of exercises (A and B) that follow the same simple-to-complex exercise structure either two or four times per week depending on the players test results. All exercises aim to have the player place the pelvis in a posterior pelvic tilt no matter from which direction the stability challenge is coming from. All exercises have been done in a circuit training format, with a 30 s break between exercises, repeated twice. As player boredom is likely an issue during the season, an updated exercise package is provided at the end of preseason.

Table 3 Range of motion (ROM)

Exercise category	Weekly session volume (two to four sessions)	Exercises	Sets and reps
Foam rolling	Rolling exercises are not mandatory and are advised to be completed if manual therapy is not received for the week.	1. Lower lumbar rolling 2. Latissimus rolling 3. Hamstring rolling 4. Adductor rolling	1×20 s in 3 regions 10 rolls per side 1×60 s 1×60 s per side
A	Negative test results: twice per week (A+A) Positive test results: four times per week (A+A+A+A)	1. Knee to chest 2. Hip flexor and hamstring slide 3. Hamstring hip flexor stretch in supine position 4. Dynamic hamstring leg raise 5. Hamstring neural flossing	1×20 2×8 per side 2×8 per side 2×8 per side 1×25

Programming design for ROM. The ROM exercises mostly focus on the hip flexor–hamstring ROM interaction and neural flossing of the sciatic nerve. However, the lumbar area has also been taken into consideration. Players complete all sets for a specific exercise with a 20 s break between sets, then transition to the next.

no further influence on the training protocol, with an exception made for the categories that include limb asymmetry measurements. Limb asymmetry will be measured in the ROM and strength categories, defined as a 15% difference between sides.[22] If an asymmetry is found within the ROM category, an extra set for all ROM exercises will be placed for the stiffer leg four times per week. If an asymmetry is found within the posterior strength category (hip extensor and/or knee flexor), an extra set within one exercise is required for the weaker leg once per week.

In the posterior chain strength category, a positive result (percentile ≤66%) corresponds to a target training volume of twice per week and a negative result (percentile >66%) corresponds to a target volume of once per week. The sprint mechanical output training category has the same percentile as the strength training category. In this case, both upper and lower horizontal force output players have the same training frequency, but the lower 66% has heavier resistance for early acceleration work, while the upper percentile predominantly works with lighter resistance. This is based on our research group's data currently in review, showing that players with elevated F0 output will likely respond less, or even not respond, to heavy loading.

Figure 6 provides more detailed aims for each training protocol category and how the test outcome, either positive or negative, determines the corresponding individualised weekly training session frequency (volume).

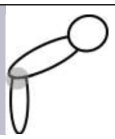
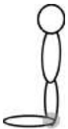
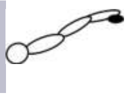
Non-individualised part of training within the intervention protocol

As briefly explained in figure 6 in the training category of 'Training for all players', as a research limitation, we found that some training stimuli will be impractical to provide on an individualised level versus a group level. These training subcategories include high-speed sprinting, post-sport ROM, triceps surae health and manual therapy (table 6). High-speed sprinting has been selected due to its potential benefits on injury risk reduction,[16] and provides an opportunity to work on the athletes' sprint 'technique'. Furthermore, this possibly contributes to improved lumbo-pelvic control (publication from our group in progress). This will be performed via different drills (table 7) and tools such as wicket hurdles. Post-sport ROM aims to relax the hamstrings and the latissimus dorsi after practice. The hamstrings are relaxed via a proposed compliance stimulus to the muscle-tendon unit via a light long contraction in a stretched position,[40] in theory counteracting the high stiffness stimuli provided from football practice. The latissimus dorsi will be relaxed by completing 10 deep breaths in a stretch relax format, with the aim to counteract stiffening and a possible anterior pull on the pelvis.[41] The third subcategory will be triceps surae health. This subcategory has been chosen based on evidence suggesting ankle and hamstring injuries may be related in linear sprinting.[42] Neural adaptations are prioritised with isometric holds at short muscle length ankle positions that are specific to sprinting (initial contact and mid-stance angles).[43] This in turn may improve stiffness and support overall improvements in sprint performance and technique.[44] Longer muscle length isometric holds have been shown to stimulate structural adaptations[43] and longer isometric holds seem to contribute to overcoming tendon stress shielding caused by repetitive microtrauma.[40 45] Therefore, to support the players' seasonal triceps surae load tolerance, long isometric holds at longer muscle lengths are used. The fourth subcategory, manual therapy, aims to more precisely influence compliance of the hamstrings and muscle tissues, possibly affecting anterior pelvic tilt. Manual therapy will be performed ideally by the team physiotherapist to the adductor magnus, erector spinae, latissimus dorsi and hamstrings. If manual therapy treatment is not available within a specific week, it is replaced by foam rolling to the same tissues (table 3).

Programming guidelines and compliance

General advice is provided to all teams on the ideal placement of training categories during one match (figures 7) and two match weeks (figure 8). Exercises have been designed considering budget differences between teams

Table 4 Posterior chain strength

Hip	**Area of focus**		**Exercises to choose from**	**Day 1 (A): sets and reps**	**Day 2 (A): sets and reps (if test result is positive)**
1—Hip	Extended (0–60°)		Hip thrust/glute bridge (bil/uni), quadruped hip extension, back extension (bil/uni)	2–3×4–8 (6–10 RM)	2–3×4–8 (6–10 RM)
2—Hip	Mid—range (60–90°)		Trapbar/sumo/traditional deadlift, 45° hyper, high sled push, high step-up	2–3×4–8 (6–10 RM)	2–3×4–8 (6–10 RM)
3—Hip	Deep (90–110°)		Squat/split squat variations, Romanian deadlift, low step-up, low sled push	1–2×4–8 (6–10 RM)	1–2×4–8 (6–10 RM)
If hip asymmetry	Extended (0–60°)		One extra set of a unilateral exercise in the extended category*	1×4–6 (6–10 RM)	
Set volume				5–7 (+1 for asymmetry)	5–7
Hamstrings				**Day 1 (B)**	**Day 2 (B)**
1—Hamstring	Hip over knee movement		Drop lunge into Romanian deadlift, perturbation stretches, straight leg dynamic cable pulls	1–2×4–6 per side (8–12 RM)	1–2×4–6 per side (8–12 RM)
2—Hamstring	Knee over hip movement		Nordic hamstring exercise, unilateral sliders, standing band curl	1–2×4–6 per side (6–8 RM)	1–2×4–6 per side (high eccentric effort)
3—Hamstring	Stiffness at knee and hip		Tantrums/bench heel kick/heel drops in lunge position	1–2×4–5 per side (tantrums in s)	
If hamstring asymmetry			One extra set of unilateral sliders†		1×4–6 (6–10 RM)
Set volume				3–6	2–4 (+1 for asymmetry)

*Asymmetry training is in the extended range of motion category as it is tested in this range.
†Unilateral sliders are chosen to correct hamstring asymmetry as it's a high load unilateral hamstring exercise reaching peak force in a similar angle as the test. Asymmetry for the hip extensors and hamstrings are advised to train on separate days to avoid excess volume sessions. Coaches choose one exercise (based on preference) from each category once to twice per week depending on test results. If asymmetry is found, complete the described extra exercise once per week. Rest between sets: 2 min. Set volume is manipulated based on athlete exposure/fatigue. RM for the given day is an approximation based on how the athlete is feeling. Athletes are advised to leave two to three repetitions in reserve in all exercises and avoid any technical sign of fatigue in stiffness exercises.
RM, repetition maximum.

to reduce bias favouring higher programme completion rates in better funded teams. Teams are advised to complete the following: lumbo-pelvic control and ROM training as a pre-warm-up; strength training so that hip strength, hamstrings, and triceps surae health are trained in the same time slot; sprint mechanical output and high-speed sprinting in combination with the team warm-up; manual therapy on off-days; and post-sport ROM after the last session of the day. Based on our ongoing discussions with the teams, there are both similarities and inevitable differences in weekly programming of the training categories due to different team cultures. For example, some teams' physical coaching staff might not be provided sufficient time to complete the entire training programme. All

Table 5 Sprint programming

Phase	Weeks	Day 1 Early acceleration(15–20 min)	Day 2 High-speed sprinting (12.5–17.5 min)	Day 3 (20–25 min) High-speed sprinting	Early acceleration	Total sprint volume Early acceleration	High-speed sprinting
Preseason: initiation	Week 1–3	A. Sprint drills 5 min B. Light/heavy sled work ×5 to 10–15m C. 5 m sprints×4, last two are races	A. Sprint drills 5 min B. Wicket sprints×3 to 45 m, 10 m rolling start before wickets, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 100%. Wicket distance: progressive	A. Sprint drills 5 min B. Wicket sprints×3 to 45 m, full acceleration start 10 m, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 100%. Wicket distance: progressive. Contrast first two wicket runs with sled sprints, total sled distance 2×15 m		130 +20=150 m (130 m sled work, 20 m first steps work)	135 +135=270 m (70 m is 100% sprinting)
Preseason: increase upright sprintingvolume, add curved sprinting	Week 4	A. Sprint drills 5 min B. Light/heavy sled work ×5 to 10–15 m C. 5 m sprints×4, last two are races	A. Sprint drills 5 min B. Wicket sprints×4 to 45, 10 m rolling start before wickets, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance: progressive. 90% runs are curved (1×left, 1×right).	A. Sprint drills 5 min B. Wicket sprints×4 to 45 m, full acceleration start 10 m, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance: progressive 90% runs are curved (1×left, 1×right). Contrast first two wicket runs with sled sprints, total sled distance 2×15 m		130 +20=150 m (130 m sled work, 20 m first steps work)	180 +180=360 m (70 m is 100% sprinting)
Pre-season: Increase early acceleration sprinting volume	Week 5–7	A. Sprint drills 5 min B. Light/heavy sled work ×6 to 10–15m C. 5 m sprints ×4, last two are races	A. Sprint drills 5 min B. Wicket sprints ×4 to 45 m, 10 m rolling start before wickets, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance, progressive from 1.5 to >1.8 m. 90% runs are curved (1×left, 1×right).	A. Sprint drills 5 min B. Wicket sprints ×4 to 45 m, full acceleration start 10 m, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance: progressive. 90% runs are curved (1×left, 1×right). Contrast first wicket run with sled sprints, total sled distance 1×15 m		135 +20=155 m (160m sled work, 30m first steps work)	180 +180=360 m (70 m is 100% sprinting)
Taper: used before post-testing or double match weeks in-season	Week 8	A. Sprint drills 5 min B. Light/heavy sled work ×3 to 20 m C. 5-m sprints ×4, last two are races	A. Sprint drills 5 min B. Wicket sprints ×3 to 45 m,10 m rolling start before wickets, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 100%. Wicket distance: progressive	REST		80 m (60m sled work, 20 m first steps work)	135 m (45 m is 100% sprinting)

Continued

Table 5 Continued

Phase	Weeks	Day 1	Day 2	Day 3 (20–25 min)		Total sprint volume	
		Early acceleration(15–20 min)	High-speed sprinting (12.5–17.5 min)	High-speed sprinting	Early acceleration	Early acceleration	High-speed sprinting
In-season: one match week structure	Same as week 5–7 structure	A. Sprint drills 5 min B. Light/heavy sled work ×6 to 10–15 -m C. 5 m sprints×4, last wo are races	A. Sprint drills 5 min B. Wicket sprints ×4 to 45 m, 10 m rolling start before wickets, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance, progressive from 1.5 to >1.8 m. 90% runs are curved (1×left, 1×right).	A. Sprint drills 5 min B. Wicket sprints ×4 to 45 m, full acceleration start 10 m, 20 m wickets, 15 m run through. Intensity: 80%, 90%, 90%, 100%. Wicket distance: progressive. 90% runs are curved (1×left, 1×right). Contrast first wicket run with sled sprints, total sled distance 1×15 m		135 +20=155 m (160 m sled work, 30 m first steps work)	180 +180=360 m (70 m is 100% sprinting)

teams have already confirmed the entire staff would collaborate to provide the highest compliance possible, but the reality is portrayed in the compliance data.

Therefore, each week the coaching staff records all completed sessions for all players within each training component. Furthermore, in training within the high-speed sprinting subcategory, all sprints instructed to be at or over 90% are reported in metres. All the data are anonymously uploaded to a server every week for verification. From here, the compliance to the intervention training protocol is calculated each week: (completed intervention sessions/intervention training target)×100. This will be done in each training category so that compliance with specific training forms can be measured. A full report of team training schedules within a typical week is provided as online supplementary material once the study has been completed.

Sample size calculation

According to the literature, about 22% of the professional football players sustain a hamstring muscle injury during a season.[5] We believe that we can obtain a relative risk reduction of 66% by implementing the multifactorial and individualised programme, which has been shown to be realistic based on previous hamstring risk reduction literature showing up to 50–70% reductions.[11–13] This corresponds to obtaining a percentage of professional football players with a new hamstring muscle injury of around 7.5%. To attain a power of 80% (α=5%) we include 93 players per group, or 186 players in total. Estimating a dropout rate of 15%, 107 players are recruited per season, or 214 players in total. The number of participants necessary was calculated using the online UCSF Clinical & Translational Science Institute application (https://www.sample-size.net/sample-size-proportions/).

Statistical analysis

Descriptive analyses of the collected data (eg, player characteristics, screening test results, injuries, sport exposure) are first performed using frequency with percentages for categorical variables and mean with SD (±SD) for continuous variables. Descriptive statistics for the total number of HMI (and percentage of all injuries), duration of time lost from sport, HMI incidence (per 1000 hour of training, match and total football practice) and burden of HMI (number of days lost due to HMI per 1000 hour of training, match and total football practice) will be provided. Compliance with the training programme will be calculated.

To analyse the impact of the HMI risk reduction programme, we perform a Cox proportional hazards regression (or Cox regression) model using ‘seasons’ (ie, control season vs intervention season) as explanatory variables and the first occurrence of a ‘new HMI’ as outcome, adjusted for age, team, body mass, height and history of HMI (previous two seasons); the unit of analysis will be the individual player and time to first event will be analysed using cumulative hours of football practice (ie,

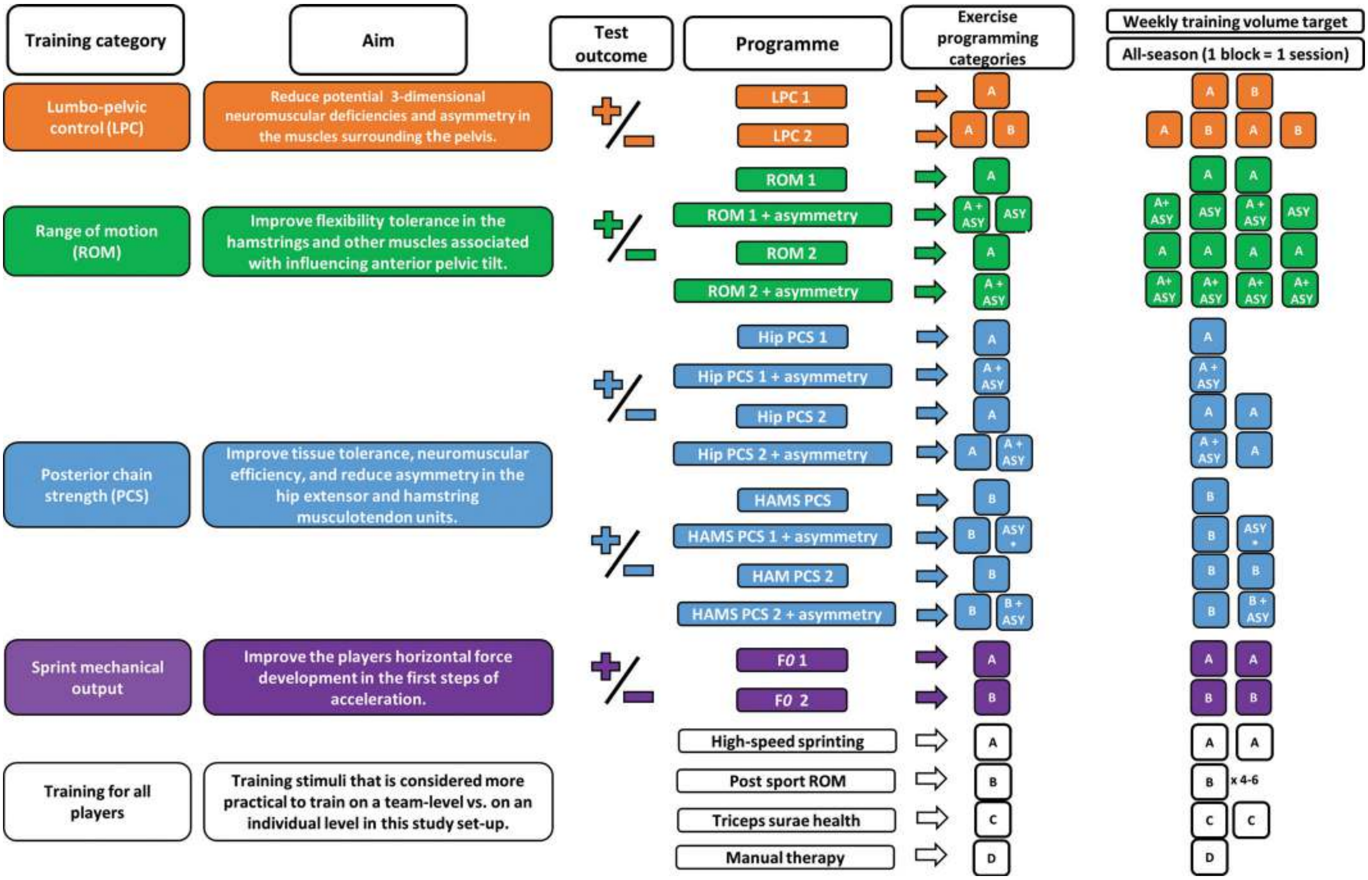


Figure 6 Brief rationale and programming methods of each training category during the entire season. In the last column, each square block represents one training session during the week. The number of blocks for every athlete are defined by the screening protocol outcomes. Target training volume is based on one match weeks. A full exercise list is provided in tables 2–7. *To avoid fatigue, hip and knee strength asymmetry are not tested within the same session.

Table 6 For all players exercises and treatments

Area of focus	Training volume (one match weeks)	Exercises
A. High-speed sprinting	Sprint drills: four times per week High-speed sprinting: twiceper week	Sprints drills and linear and curved sprinting with/without wickets. See tables 5 and 7 for programming.
B. Post-sport ROM	Once every training day and post match	Hamstrings: 30 s partner assisted very light isometric holds in the straight leg raise position Latissimus dorsi: 10 deep breaths in an overhead hanging position (TRX/ rubber bands)
C. Triceps surae health	Twice per week	All done in rear elevated split position with barbell or without weight Set 1: High plantar flexion 1×10–30 s Set 2: 90° dorsiflexion 1×10–30 s Set 3:110° dorsiflexion 1×10–30 s
D. Manual therapy	Once per week	1. Erector spinae 2. Adductor magnus 3. Latissimus dorsi 4. Hamstrings

training and competition) as a timescale. The HR with a 95% CI will be presented for each variable, and assumption that the HR will be constant over time will be tested.

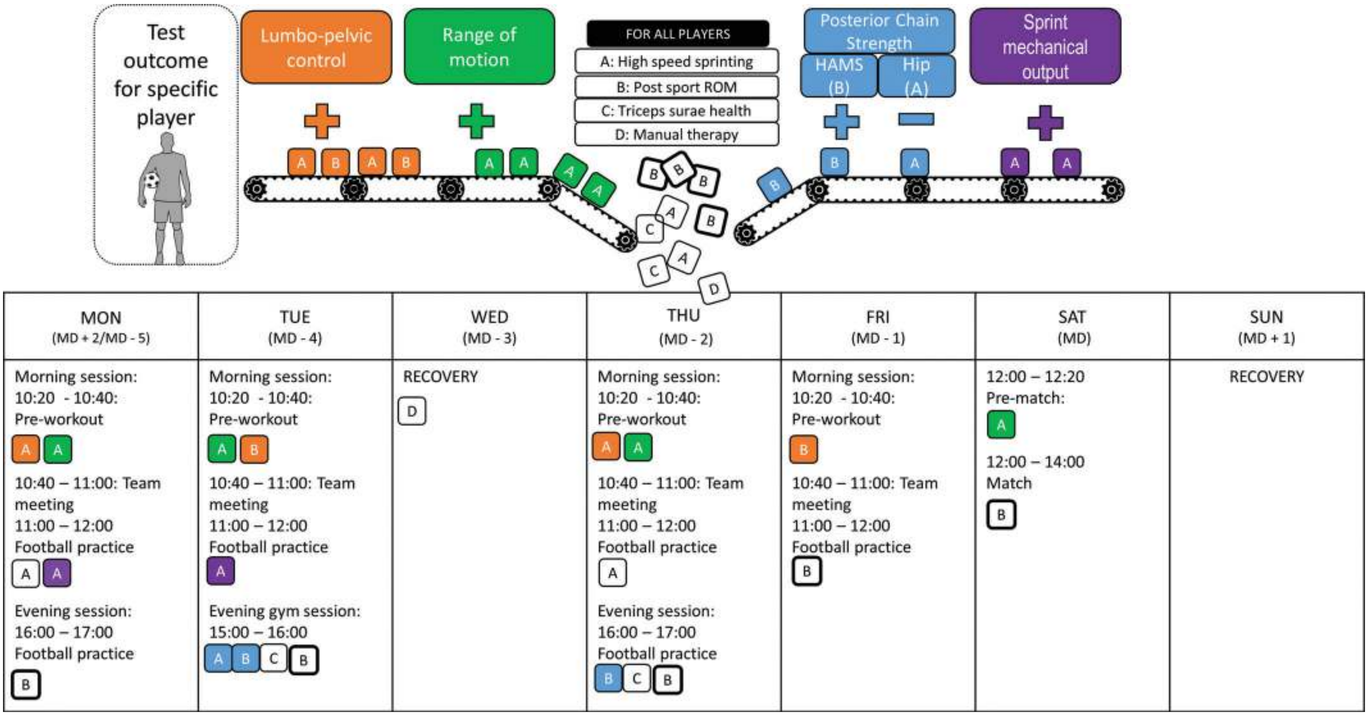
Due to our main research question not being related to the changes in screening tests, we have not completed null hypothesis significance test statistics. However, to improve the relevance of discussions for clinicians, magnitude of difference statistics (effect size) will be performed for all screening categories between the three testing sessions.

ETHICS AND DISSEMINATION

This study has received two separate ethical approvals. The study protocol for the injury and sport exposure data collection used in the control season was reviewed and approved by the Saint-Etienne University Hospital Ethics Committee (Institutional Review Board: IORG0007394; IRBN322016/CHUSTE). This ethical approval was obtained in 2016 for conducting multicenter prospective injury data and sport exposure data collection but did not include the intervention. The study protocol for the intervention season was approved separately by the Central Finland healthcare District (U6/2019). Applying for one ethical approval that permitted for both prospective data collection from the 2019 control season followed by an intervention season was not possible, as the opportunity to conduct an intervention among professional football players was first provided in 2019, while prospective injury data and sport exposure data collection were in process. Thus, the ethical approval

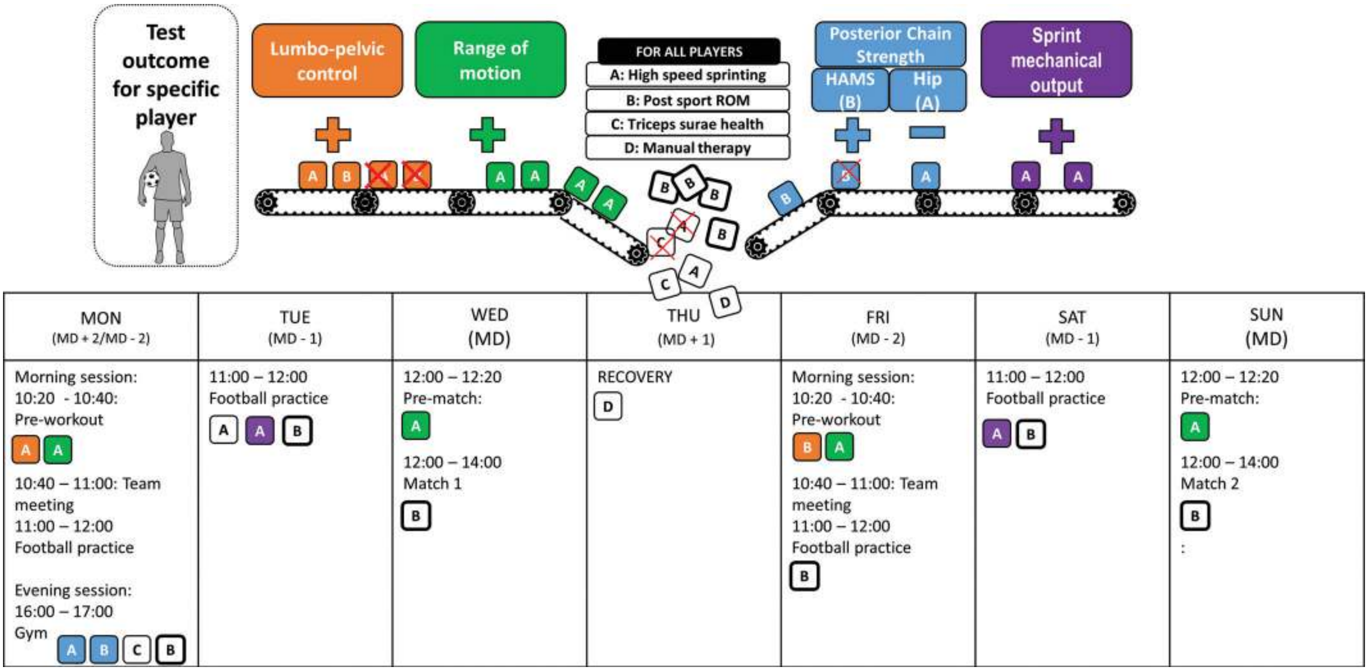
Table 7 Sprint drills programming

Week	Day	Exercises
Week 1–2	All 3 days	A-skip progressions, Pogo jumps (sagittal and lateral), dribble bleeds
Week 3–4	1	A-skip progressions, unilateral pogo jumps, dribble bleeds
	2	A-skip progressions, lateral A-skips
	3	Same as day 1
Week 5–6	1	A-skip progressions, lateral A-skips, scissors (high frequency)
	2	A-skip progressions, skip jumps, dribble bleeds
	3	Same as day 1
Week 7–8	1	A-skip progressions, lateral A-skips, scissors (progressive: high frequency to power)
	2	A-skip progressions, skip jumps, dribble bleeds, pogo jumps
	3	Same as day 1
In-season	1	A-skip progressions, lateral A-skips, scissors (progressive: high frequency to power to dribble bleeds)
	2	A-skip progressions, pogo jumps, skip jumps
	3	Same as day 1



MON (MD + 2/MD - 5)	TUE (MD - 4)	WED (MD - 3)	THU (MD - 2)	FRI (MD - 1)	SAT (MD)	SUN (MD + 1)
Morning session: 10:20 - 10:40: Pre-workout A A 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice A A Evening session: 16:00 – 17:00 Football practice B	Morning session: 10:20 - 10:40: Pre-workout A B 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice A Evening gym session: 15:00 – 16:00 A B C B	RECOVERY D	Morning session: 10:20 - 10:40: Pre-workout A A 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice A Evening session: 16:00 – 17:00 Football practice B C B	Morning session: 10:20 - 10:40: Pre-workout B 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice B	12:00 – 12:20 Pre-match: A 12:00 – 14:00 Match B	RECOVERY

Figure 7 Example week for individualised and team programming for one match per week (on Saturday in this example). A hypothetical scenario is demonstrated based on one player's screening results. Each team finds slightly different solutions to fit in the training blocks, which are discussed in the main publication.



MON (MD + 2/MD - 2)	TUE (MD - 1)	WED (MD)	THU (MD + 1)	FRI (MD - 2)	SAT (MD - 1)	SUN (MD)
Morning session: 10:20 - 10:40: Pre-workout A A 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice Evening session: 16:00 – 17:00 Gym A B C B	11:00 – 12:00 Football practice A A B	12:00 – 12:20 Pre-match: A 12:00 – 14:00 Match 1 B	RECOVERY D	Morning session: 10:20 - 10:40: Pre-workout B A 10:40 – 11:00: Team meeting 11:00 – 12:00 Football practice B	11:00 – 12:00 Football practice A B	12:00 – 12:20 Pre-match: A 12:00 – 14:00 Match 2 B :

Figure 8 Example week for individuali'sed and team programming for two matches per week (Wednesday and Sunday in this example). On double match weeks, training sessions will be to different degrees sacrificed for improved recovery (red crosses).

for the intervention protocol was accepted at the end of the control season (2019). Therefore, our present study relies on two different ethical approvals: one for prospective data collection only corresponding to the first part of the study and the control season, and other for the intervention corresponding to the second part of the study and the intervention season. This study will be conducted in accordance with the Declaration of Helsinki.

Prior to enrolment in the study, all participants were asked to give their informed consent. The participants can decide at any time to be released from the study, and they are informed of this in the information documents. If accepted, data obtained during this study are used by the research team until their papers are accepted for publication, but for a maximum of 5 years, after which all materials will be destroyed. Participation is entirely voluntary, and participants may refuse any test or exercise at any time and for any reason. Participation, suspension or exclusion from this research study will in no way affect the position of recruits in their team community.

Results are published in a peer-reviewed sport and exercise medicine journal, regardless of the findings related to the number of positive or negative hamstring injuries sustained between the two seasons. In order to enhance knowledge translation of the findings, a multimodal approach will be used for dissemination; findings are presented at conferences, and multimedia resources (eg, infographics, animations, videos, podcasts and blogs) are created to share findings via various social media platforms and through media release.

CONCLUSIONS

Although there has been a large effort to include up to date evidence-based exercises for HMI risk reduction,[4 8 46] the aim of this study is not to answer what specific exercises (and their respective implementation strategies) are optimal. Our aim is to focus on the bigger picture and, thus, test the possible functionality of a specific multifactorial and individualised approach conceptualised for HMI risk in professional football.

There is consensus among sport scientists that multifactorial programming is necessary for hamstring injuries,[4 9–12] and we hope this study provides an interesting first step despite inevitable methodological limitations. Ideally, the teams are randomised to either a multifactorial programme or both multifactorial and individualised programme. However, this is difficult to create in real-life professional settings as many teams likely already have multifactorial and individualised protocols in use to varying extents. Thus, it is likely implausible in many cases that professional teams would agree to complete an intervention where their current protocols would be downgraded for the benefit of research. The format in which the screening protocol data is used to identify players at risk and assign individualised training protocols could be considered to be another limitation. Another approach would use non-linear machine learning algorithms based on data from multifactorial testing, emphasising the idea that no single data point is important in isolation.[47] These machine learning models are compatible with data that are considered important for most injuries in football, such as body mass, age, injury history, workload management and wellness scores.

Ideally, before conducting such an intervention, the screening protocol should be properly tested for its accuracy in identifying risk using such models with an entire control season devoted to it. In addition, since our aim is to maximise the dissemination and implementation of the intervention programme in the professional football community, we prefer using a relatively straightforward approach. This also provides an approach compatible with the data processing skills of most practitioners in real-life professional football. Therefore, we use the team percentile method, and future follow-up studies should analyse the interest of more advanced prediction models. If the protocol is successful, the current approach may work in other football populations with similar baseline values. However, it is inevitable that this approach presents its limitations in the form of producing false negatives and not being able to appropriately address players that are true positives. Additionally, updates and replacements to testing methods are encouraged within each testing category as advances in validated technology take place. Furthermore, it is important to state that this type of musculoskeletal multifactorial approach should ideally be a part of a biopsychosocial approach used for all injuries.[47] Finally, we acknowledge the fact that two separate ethical approvals were needed for one research project.

The strength of this study is its potential for direct practical implementation in teams with varying resources and budgets. We expect that reaching appropriate compliance is one of the greatest challenges facing this project. Most literature indicates that compliance is a clear problem in injury risk reduction protocols and likely explains the lack of results.[2 9 46 48] Player buy-in will be paramount, which itself will be mediated by the coaching practices within each team. We are optimistic that an injury risk reduction programme that considers the individual, both from a risk reduction and performance standpoint, might increase the potential for long-term compliance.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- This study helps to demonstrate the initial value of individualised training programmes based on a multifactorial hamstring screening protocol designed to reduce HMI in professional football.
- All testing and training are implemented in the field. Therefore, if the approach is successful in reducing HMI (study outcome), it has a high potential for direct transfer into practice. This includes free video links of all exercises once the study is completed.
- Normative data from the screening tests are published and provide a good initial reference database for practitioners looking to use the same tests.
- This study lacks randomisation and blinding, and therefore, at best provides good but not the highest level of evidence for validity of the HMI risk reduction programme.
- Comparing HMI between two separate seasons increases the risk of confounding factors affecting result interpretation.

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5.3. ANALYSIS AND CONSIDERATIONS OF THEME III

The first aim with theme III was to publish a protocol paper to describe our HMI risk reduction intervention approach. The second aim was to conduct and publish the intervention study results. Unfortunately, only the protocol paper was published (Lahti, Mendiguchia, *et al.*, 2020). The intervention started as planned in the beginning of 2020 and the first round of testing was successfully completed in all five teams (n = 94). Unfortunately, the Covid-19 pandemic led to the 2nd round of testing (planned for march-april) being cancelled. The virus led to the Finnish Premier League starting first in June, which was two months after the normal starting date. This made the season ~30 % shorter (end date was similar at the end of October), with a substantially higher match frequency. As the comparison was a single control season (2019), it was paramount that they were similar in structure to be valid. Thus, the study was postponed for potentially the next season (2021). We decided to publish the available data what we had within the frame of this thesis timeline. This included two tables of results from the first screening round in 2020. In Table 3.1 (Appendix 3), we present the averages and 95 % confidence intervals for all screening tests from 94 professional football players. The table results are interesting to compare to the normative data published in study I, as the practitioner testing the players was the same (Johan Lahti). However, it is important to emphasize that this data was taken at two different points of the 12-week pre-season. Study I data was based on the end of the pre-season whereas the intervention data was from the beginning of pre-season. The comparison showed that nine out of 11 tests had only small effect size differences (range: -0.16 – 0.50 ES), whereas both strength tests (knee flexor and hip extensor) were moderately higher (0.63 – 0.75 ES) during the 2020 season. It is difficult to say to what extent the difference in maximal strength is due to measurement error as we did not test inter-day reliability within a professional setting in the frame of this thesis. Our pilot data from a less experienced cohort showed that dynamometer minimal detectable change can be up to 15 % between sessions (Lahti *et al.*, 2021), corresponding to previous literature (van der Made *et al.*, 2019). The 2020 season measurement results for strength were 12-13 % higher compared to the 2019 season. Pre-season is initiated after a two-month off-season, where all teams reported targeting development of basic athletic qualities such as maximal strength to the available players (i.e., some players were first drafted to the teams in the end of the off-season). Thus, testing at the beginning of the pre-season one can assume that strength levels may be good. The pre-season can be considered a fatiguing time, with the aim to prepare the players for the season more specifically. Therefore, it is possible that drops in performance can take place. In fact, most

HMI in study I took place in the beginning of the season, which could be partially related to fatigue from the pre-season and a peak in physical load due to official games resuming. However, as we do not have control season data from the beginning and end of the pre-season, we can only speculate if this is the case. Despite this, we find this observation supportive in emphasizing the importance of aiming to maintain high levels of performance derived from the off-season. Also, whenever possible, continuing to increase performance during the pre-season should be the target, as we achieved in study II.

In Table 3.2 (Appendix 3), the percentile cut-offs in each training category are presented per team. Table 3.2 also includes the number of players with asymmetries per team. Finally, Table 3.2 also includes whether there were significant between team baseline differences. This would assist to understand whether there were high fluctuations in negative/positive screening result thresholds between teams. There were two tests that included significant percentile baseline differences, with one team showing higher average levels of sprint kinematics (defined by higher Kick-back test scores), and one team showing lower average hip extensor strength scores. There was also a significant baseline difference with the number of players that had Jurdan test range of motion asymmetries. This was likely due to that one team had zero asymmetries and another six. With roughly 20 professional players per with different backgrounds, it would be strange that no significant baseline differences in team percentiles would be seen. However, only three baseline differences out of 11 tests likely speaks to the degree of specialization of this cohort. This means that football players within a specific league can be considered relatively homogenous in athleticism. Thus, the simple percentile method used in the intervention does not seem to lead to substantial differences in treatment.

6. DISCUSSION

6.1. MAIN FINDINGS OF THE THESIS

The general aim of this thesis was to contribute to contribute to the HMI risk reduction literature within professional football. This work was divided into three themes – the main aims and subsequent findings from which are as follows:

Theme I. Here we introduced a musculoskeletal hamstring screening protocol and to test its relevance in identifying players at increased HMI risk, thus focusing the first two stages of the TIP model. 161 professional football players were recruited to conduct two rounds of multifactorial musculoskeletal testing (11 tests) during the season to control for possible changes in variables (Jiménez-Reyes *et al.*, 2020; Moreno-Pérez *et al.*, 2020). The screening protocol included two novel tests novel to the published literature, the "Jurdan test" and the "Kick-back" test. Evaluating HMI burden was important to ensure relevance of the epidemiological circumstances between the chosen cohort. Accordingly, we found that the epidemiological situation was comparable to previous literature (Ekstrand *et al.*, 2011, 2013, 2016; Tabben *et al.*, 2021), with 14.1 days absent per 1000 hours of football exposure. In Section 3.3, we present additional supportive epidemiological data from our cohort. In Figure 24, present the injury burden of the top-10 injuries in the cohort, which supports that HMI continues to be one of the main injury dilemmas among professional football players. Specifically, there were a total of 17 index HMI during the season. No specific screening test score was associated with increased HMI risk when considering injuries from the entire season ($p > 0.05$). When including only injuries between screening rounds one and two (end of pre-season and mid-season, ~90 days), lower $F0$ was significantly associated with increased HMI risk (n=14, hazard ratio [HR], 4.02 (CI95 %: 1.08 - 15.0, $p = 0.04$). Given an association between injury incidence and $F0$ was detected in a relatively small sample, its relevance for HMI risk assessment might be stronger when applied at a larger scale (Bahr and Holme, 2003). Unfortunately, the low sample size did not allow for multivariable statistical analyses, therefore relevance of the 11 tests could only be tested in isolation.

Theme II. Our aim in theme II was to focus on training horizontal force capacity in professional football players and gain practical insight for the final TIP model stage: to *intervene*. As newly proposed risk reduction approaches can be practically challenging to implement (Nassis *et al.*, 2019; van der Horst *et al.*, 2021), piloting the trainability of specific variables within the desired cohort was rationalized to provide valuable insight into its feasibility. With the results of study I and previous literature (Mendiguchia *et al.*, 2014; Mendiguchia *et al.*, 2016; Edouard, Lahti, *et al.*, 2021), our aim was to test the trainability of F*0* during the pre-season. Heavy resisted sprint training was hypothesized as an effective and practical solution, as it can be conducted on-field and provides high horizontal force at low velocities stimulus (i.e., relevant to F*0*). To this end, two professional football teams were recruited for an 11-week training intervention (n = 32). One of the teams was selected for a control group, and the other to participate in a targeted intervention. The intervention team was further divided into two sub-groups to evaluate two different heavy resisted loads for effectiveness. This included a 50 % velocity loss (VL) load and a 60 % VL load. Alongside mechanical output measurements (i.e., sprint force-velocity profile variables), alterations in sprint posture during and after the resisted sprint training sessions were also studied. This would allow for a more holistic assessment of the potential long-term influence of heavy resisted sprinting. The Two-way ANOVA results showed there were no significant between-group differences for F*0* ($p = 0.08$), and that adaptation potential was significantly associated with initial F*0* levels in both heavy resisted groups ($r = -0.59$, $p < 0.05$). This association is in line with the results from recent literature (Lahti, Jiménez-Reyes, *et al.*, 2020), and is visualized in Section 4.3, Figure 25. This finding emphasizes the importance of individualizing training. No long-term alterations were seen in sprint posture despite the substantial immediate technical influence of heavy resisted sprinting, when considered in the classical manner. The 50 % VL load improved significantly horizontal peak power (Effect size: 1.16) and 10-m sprint performance compared to the control group (Effect size: 1.03). This might reflect that a resistance leading corresponding to a 50 % velocity loss provides a slightly broader benefit for sprint performance compared to 60 % velocity loss. The results demonstrate that heavy resisted sprint training appears to be a valid and a feasible tool to improve horizontal force capacity in players with lower F*0* in a professional football context.

Theme III. Our aim in theme III was to finally move directly into the final stage of the TIP model: to *intervene*. We developed a multifactorial and individualized approach for HMI risk reduction, which was built based on the screening protocol presented in study I. The intervention included also non-individualized training components, which were based on current evidence and anecdotal observations from highly experienced practitioners. A total of five Finnish premier league teams enrolled in the study, with goalkeepers excluded due to the low HMI risk (player cohort, n = 94). The coaching staff responsible for implementing the approach within each team were extensively educated so that they could perform and teach the exercises effectively. The same coaches were also responsible for injury, sport exposure, and compliance data collection. The first round of screening testing was completed successfully in

January 2020. However, the Covid-19 pandemic led to the study being postponed due to insoluble consequences to the study design. We publish the preliminary data that was taken before the pandemic in January 2020 (i.e., the first screening round). Here we demonstrate that the percentile thresholds proposed were relatively homogeneous among the teams.

Therefore, the main findings from themes I-III are:

1) HMI continues to be of paramount concern in professional football;
2) No isolated screening tests were associated with HMI during the entire season;
3) When assessing for HMI closer to testing, $F0$ was associated with increased HMI risk;
4) Heavy resisted sprinting is a feasible method of improving $F0$ in professional players with low initial levels without adverse effects on running kinematics;
5) The screening protocol was accepted and successfully implemented in the recruited football clubs training environment, both from a screening and training perspective;
6) The percentile method used to individualize the HMI risk reduction program does not seem to lead to highly heterogenous differences between the included teams.

6.2. LIMITATIONS

One of the main limitations of this thesis is sample size and lack of randomization, which increases the difficulty of making sustainable inferential statements. This is a common problem found in professional cohorts (Ruddy et al., 2019). In study I, our study power was reduced due to two professional teams dropping out from the experimentation. Bahr and Holme, (2003) proposed that ~20-50 injuries are needed to find stronger relationships and up to 200 for weaker relationships. As one can imagine, ~50-200 HMI likely requires collaboration between multiple research institutions – the likes of which was not achieved in this thesis work. However, data does not have to be collected simultaneously in different cohorts to be useful. Instead, it can be made available and combined into a retrospective dataset (Ruddy *et al.*, 2019). Nevertheless, 17 index injuries were sufficient to indicate relevance of F*0* in a professional setting, which may reflect its strength to detect associations on a group-level. Some analyses within study II were likely underpowered, which is potentially best demonstrated in Figure 2 in the second study, where early acceleration sprint-performance improvements were highly comparable between loads. However, our main aim within study II for this thesis was to test the utility of heavy resisted sprinting for improving F*0*, which was demonstrated on an individual level. In any case, lower study power and other methodological limitations (e.g., a lack of randomization) indicates a need for replication.

For study III, the lack of randomization lowers certainty in the evidence. In hindsight, it would have been interesting to compare a multifactorial approach vs. a multifactorial and individualized approach in form of a one-season RCT. However, this would have required more teams than five to detect clear differences and likely necessitated some teams downgrade ongoing risk reduction approaches (e.g., teams that were randomized into the multifactorial group and were already using their own methods of individualization). Prospective cohort studies are more realistic within such contexts (Arnason *et al.*, 2008; Suarez-Arrones *et al.*, 2021), even if comparing to only one control season makes the results less robust. However, if the control season's injury statistics are highly alike to previous literature (which was the case, i.e., study I), and the control and intervention seasons are similar in length, match frequency, and in main confounding factors for players (previous HMI, age), then they can be considered comparable. Based on comparisons of the 2019 and 2020 pre-season data, this was the case with our project.

In the future, the percentile method chosen to individualize groups will likely be considered simplistic. Due to the complexity of injuries (Bittencourt *et al.*, 2016; Ruddy *et al.*, 2019), the results will inevitably lead to some players assessed as false positives or false negatives. Therefore, it was important that in either case of incorrect categorization, the likelihood of detrimental effects is minimized or mitigated. Notably, while a false positive player would train more than required in a specific category, in most cases this would likely lead to either maintenance of results or even improvements in performance (e.g., more lumbo-pelvic control or strength training could potentially assist sprinting speed) (Mendiguchia *et al.*, 2021). Vice versa, a false negative player would likely be safe as all multifactorial training categories remained in the base program. For now, the percentile method was considered appropriate for a workable balance between the data analysis skills present within the typical research team and club setting. It also could assist in engaging players into the physical training, as individualizing programs should increase motivation (Chatzisarantis and Hagger, 2007). Currently, complex non-linear data analysis systems are not necessarily user-friendly and require strong statistical knowledge to implement and understand (Ayala *et al.*, 2019). Nevertheless, since they very likely provide superior results, their evolution in functionality is inevitable. However, as mentioned in the protocol paper (Lahti, Mendiguchia, *et al.*, 2020), our target was maximizing the circulation and implementation of the intervention format within the current professional football club ecosystem. Towards this aim, a relatively straightforward approach was deemed preferable.

The final main limitation in this thesis is the technology and the interrelated methods used to assess players at risk for HMI. The advancement speed and competition in testing technology is currently high. Consequently, tests selected just three years earlier (i.e., the design schedule of a typical Ph.D thesis) may not be as relevant when research results are finally compiled, written, submitted, and published for public consumption. While some tests are potentially more timeless than others (e.g., range of motion), others can be much more sensitive obsolescence due to technological advancements (e.g., movement sensors for dynamic pelvic motion). Therefore, it is important to discuss this limitation in each paper and to promote technological advancement so that practitioners can obtain more accurate results in an accessible manner. Therefore, the more timeless proposal of this thesis is related to the testing categories (i.e., range of motion, lumbo-pelvic control, posterior chain strength, and sprint mechanical output), and not the tests *per se*. Our hypothesis is that these testing categories are partially independent from each other and thus will continue to provide valuable structure irrespective of technological advancements.

6.3. RESEARCH PERSPECTIVES

One of the most valuable outcomes from well-designed and implemented research is the creation of new questions. Despite the limitations, this thesis yielded multiple interesting questions that will hopefully drive future research. In terms of testing methods, exciting developments have taken place during this thesis. For example, F*0* has been recently proved reliable to test in-situ (i.e., during football practice via a specific processing method of position data provided by modern GPS units) (Morin *et al.*, 2021). This shifts these types of testing from screening to monitoring, or even "testing without testing". Although completely moving into a "testing without testing" format is not likely realistic, methods that increase the likelihood of frequent testing should be promoted. For strength testing, using fixed dynamometry will likely be more reliable compared to manual (Wollin, Purdam and Drew, 2016). To our knowledge, this hypothesis has not been studied in high-level football populations, which would be especially important to assess for hip extension strength based on our observations from study I. We observed difficultly in holding reliable positions for stronger players (~ >350 N), which likely explained the higher error between repetitions (Appendix 1, Table 1.1). However, the problem of testing knee flexion and hip extension in isolation begs discussion, as a system is not necessarily the sum of its parts (Bittencourt *et al.*, 2016). As the hamstring muscles are both primarily knee flexors and hip extensors, using a test that simultaneously stimulates torque at both joints seems logical. Electromyographic analysis has shown that hamstring excitation increases if a knee flexion isometric contraction is coupled with a hip extension contraction (Hegyi *et al.*, 2021). As the aim with maximal strength testing is to gain insight of the hamstring muscles load tolerance, innovation for tests that utilize both joints simultaneously should be promoted. For the lumbo-pelvic category, we used both direct and indirect measurements with the aim of gaining insight of the players dynamic APT during sprinting on the field. Future technology may allow for similar sensors as we used for the walk-test to be on the player during football participation. This represents an important update, as the players baseline pelvic motion values may not necessarily be problematic, but instead the changes that may be induced by fatigue from football exposure (Small *et al.*, 2009). In the walk-test, we used a composite score from the sagittal (APT) and frontal plane (pelvic obliquity) to improve reliability (Lahti *et al.*, 2021). However, although both may be relevant risk factors for HMI (Franettovich Smith *et al.*, 2017; Schuermans, Damien Van Tiggelen, Palmans, Danneels and Witvrouw, 2017; Kenneally-

Dabrowski *et al.*, 2019), APT and pelvic obliquity are to a largely independent from each other (r = 0.20). Consequently, future studies should aim to assess them as separate risk factors.

Regarding the concept of "testing without testing", with appropriate equipment, strength testing can also be done as a form of training during gym sessions, or rough range of motion testing during group warm-ups. This would likely assist in time management and controlling for fluctuations in performance during the season (Jiménez-Reyes *et al.*, 2020). Furthermore, test improvements do not necessarily have to include technological advancements. For example, simple knee lift lumbo-pelvic tests can effectively assess ACL injury risk (Leppänen *et al.*, 2020), albeit via 3D motion analysis (Vicon systems). Thus, replication is needed to show whether clinicians can visually spot similar movements. Our novel "Jurdan test" was an example of this, where conducting the test doesn't require expensive technology and may provide a broader view of hamstring muscles active extensibility. However, as our results from study I were unclear, larger samples sizes and multivariable statistical models are needed to determine its validity. Similarly, the same applies for the "Kick-back" test, which would benefit from automated approaches to streamline testing in place of inputting the angles manually.

The evolution of multifactorial individualization approaches is important, both in HMI risk and performance-oriented approaches. Non-linear advanced machine learning approaches will help to assess multiple data points and accordingly more accurate conclusions can be made per player (Ayala *et al.*, 2019). This includes considering musculoskeletal, cardiorespiratory, and psychological variables (Ayala *et al.*, 2019), and ideally risk factors for all common injuries. Thus, becoming inevitably a highly holistic approach. At some point, it is obvious that one can focus on the HMI burden in disproportion compared to other injuries. It is also important to note that a large focus on HMI risk reduction training may lead to new types of injuries in other body parts, which are difficult to predict. For holistic solutions to evolve faster, multiple institutions should work together to collect data from multiple categories of interest. Also, resources should be devoted to staff and player motivation, in the aim of potentially changing harmful habits or unsustainable cultural structures. As compliance is usually reported as an issue (Bahr, Thorborg and Ekstrand, 2015; Nassis *et al.*, 2019; van der Horst *et al.*, 2021), creating an appropriate model to assist in dissemination of new ideas should be created. Large sample sizes would also help to answer whether using both multifactorial and individualized training is better than just multifactorial.

6.4. CONCLUSION

This thesis provides valuable information for future HMI risk reduction research, albeit its experimental design and subsequent findings complicated by the Covid-19 pandemic. Within the challenging context of professional sport, we have presented novel tests, piloted their initial association with group-level HMI, shown important longitudinal findings in training horizontal force using heavy resisted sprinting, and proposed a novel multifactorial and individualized approach for HMI risk reduction. All of which is extensively rationalized, visualized, and discussed.

Our results suggest at least testing whether F*0* is useful to monitor and train for HMI risk reduction in professional football, assuming it's one component of a multifactorial approach. We also promote innovation of regular testing and training within a multifactorial and individualized context. For now, however, caution is warranted in forming direct practical applications based on our results due to methodological limitations. Most importantly, our proposed protocol must be tested to provide the most valuable information that our research team can offer for HMI risk reduction

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8. APPENDICES

8.1. APPENDIX 1 (THEME I)

Table 1.1. Absolute and relative within-session intrarater reliability of the screening protocol tests

Test Category	Test	ICC	95%CI		ICC level	CV %			MDC	MDC %
Lumbo-pelvic control	Walk test (°)	0.95	0.93	0.97	Excellent	3.57	3.10	7.8	1.67	18.1
	Kick-back test (°)	0.87	0.80	0.91	Excellent	2.66	1.44	3.87	13.10	8.98
Posterior chain strength	Knee flexor strength (N.kg^{-1})	0.96	0.95	0.97	Excellent	2.58	1.68	3.48	25.0	8.70
	Knee flexor strength asymmetry (%)	0.48	0.31	0.62	Fair	(N/A)				11.2
	Hip extensor strength (N.kg^{-1})	0.90	0.85	0.93	Excellent	4.29	2.09	6.49	61.1	18.4
	Hip extensor strength asymmetry (%)	0.43	0.25	0.58	Fair	(N/A)				19.3
Range of motion	ASLR (°)	0.89	0.84	0.92	Excellent	2.84	1.95	3.74	8.42	9.64
	ASLR asymmetry (%)	0.42	0.24	0.57	Fair	(N/A)				12.8
	Jurdan test (°)	0.95	0.92	0.97	Excellent	2.85	1.90	3.81	7.44	9.49
	Jurdan test asymmetry (%)	0.43	0.25	0.58	Fair	(N/A)				13.7
Sprint mechanical output	Maximal theoretical horizontal force (N.kg^{-1})	0.87	0.82	0.91	Excellent	2.82	1.68	3.95	0.60	8.02

Table 1.2. Video links for the two novel screening tests

Test	Video link
The Kick-back test	https://www.youtube.com/watch?v=ygXmiamHfp0
The Jurdan test	https://www.youtube.com/watch?v=9uTmHvkXsCQ

8.2. APPENDIX 2 (THEME II)

Table 2.1. The intervention teams weekly schedule.

Day	Time	Week -1 1-6.1	Week 0 7-13.1	1th Week 14-20.1	2th Week 21-27.1	3th Week 28.1 – 3.2	4th Week 4-10.2	5th Week 11-17.2	6th Week 18-24.2	7th Week 25.2 – 3.3.	8th Week 4.3-10.3	9th Week 11.3 – 17.3	10th week 18.3 – 24.3	11 week 25-31.3
MON	AM		Tec	Tec	Tec	SP			SP			Tec	SP	Tec
	PM		Tec	Tec	Tec	Tec	Tec	Rec / Tec	Tec		M	Tec	Tec	Tac
TUE	AM		Endurance Test	Tec / Tac / CG	RE / Tec / / Tac / CG	RE / Tec / / Tac / CG	RE / Tec / / Tac / CG	RE / Tec / / Tac	RE / Tec / / Tac / CG		Rec	RE/Tec / Tac / CG	RE/Tec / Tac / CG	Tec / tac / CG
	PM			MB	MB	MB	MB	MB	MB		Tac	MB	MB	MB
WED	AM		Rec	Rec	Rec	Rec	Rec	Rec	Rec		Tac		Rec	Rec
	PM											Rec		
THU	AM	Tec	LB	LB	LB	LB	LB	LB	LB		Tec / Tac	LB	LB	LB
	PM	Tec	Tac	RE / Tac	RE / Tac	RE / Tac	RE / Tac	RE / Tac	RE / Tac		Tac	RE/Tac	Tac	Tac
FRI	AM	LB	Tec				Tec							Tac
	PM	Tec / Tac	Tac	Tac	Tac	Tac	Tac	Tac	Tac	RE / Tec	M	Tac	Tac/CG	
SAT	AM	Familiari-zation and sprint testing	Familiari-zation and sprint testing				OFF				Rec			Sprint tests
	PM			M	M	M		M	M	Tec / Tac		M		
SUN	AM						M			Tec / Tac				
	PM		a							Tac				M
Training hours		6h 30min	9h 40min	10h	9h 35min	9h 30min	9h 20min	8h 15min	9h 25min	5h 15min	7h 15min	9h 50min	9h 40min	8h 30 min

Values: Tec = Technical Training, Tac = Tactical Training, LB = Lower Body, MB = Mixed full body training, CG = Condition Games, Rec = Recovery Training, SP = Spinning, RE = Resisted Sprinting Training, M = Match.

Table 2.2. The control teams weekly schedule.

Day	Time	Week 0 7-13.1	1th Week 14-20.1	2th Week 21-27.1	3th Week 28.1 – 3.2	4th Week 4-10.2	5th Week 11-17.2	6th Week 18-24.2	7th Week 25.2 – 3.3.	8 th 4.3-10.3	9 th 11.3 – 17.3	10 th 18.3 – 24.3	11 th 25.3–31.3	12 th week 1-7.4.2019
MON	AM	Tec	Tec	Tec	Tec	Tec	Individual program	Tec	Tec	Tec	Tec	Tec	Tec	Tec
	PM	MB	LB											
TUE	AM	Tec (small pitch)	Tec	Team endurance and speed testing	Tac/CG	Tac/Tec	Individual program	M	Tec/Tac	Tac/CG	Tec/Tac	Tec	Tec/Tac	Tec/Tac
	PM		MB		LB	LB			MB	MB			MB	MB
WED	AM	Tec	Tec	Tac	Tac	Tac/CG	Individual program	MB	Tac/CG	Tec/Tac	Tac/CG	Team endurance and speed testing	Tac/CG	Tac/CG
	PM													
THU	AM	MB	MB	MB	MB	MB	Tec/Tac	Tec	MB	MB	MB	Individual program	MB	MB
	PM													
FRI	AM	Sprint tests	M	Tac	M	Tac	Tac LB	Tec	Tec	M	Tec	Individual program	Tec	Sprint tests
	PM	Tac/CG												Tec
SAT	AM	MB	Rec	M	Rec MB	M	MB	M	M	Rec	M	Individual program	M	Tec
	PM													
SUN	AM	Rec	Rec	Rec	Rec	Rec	Rec	Rec	Rec	Rec	Rec	Individual program	Rec	M
	PM													
Training hours		8 h 20 min	7 h 20 min	7 h 30 min	7 h 45 min	8 h 45 min	7 h 50 min	5 h 10 min	8 h 30 min	8 h 20 min	8 h 30 min	7 h 45 min	8 h 30 min 9	8 h 30 min

Values: Tec = Technical Training, Tac = Tactical Training, LB = Lower Body, MB = Mixed full body training, CG = Condition Games, Rec = Recovery Training, M = Match

Table 2.3. Within-sprint reliability of kinematics and spatiotemporal variables during early acceleration.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.00	0.01	0.01	0.01	0.50	1.03	1.94	1.87	0.01	0.23	0.81	1.86	0.86
TE lower	0.00	0.01	0.01	0.01	0.36	0.74	1.39	1.34	0.01	0.17	0.58	1.33	0.62
TE upper	0.00	0.02	0.02	0.02	0.82	1.70	3.21	3.09	0.02	0.38	1.34	3.07	1.42
MDC %	2.59	0.70	2.84	-40.96	1.48	6.13	5.17	3.31	3.63	1.37	4.92	3.05	2.83
CV %	0.28	0.09	0.57	-63.37	0.37	1.60	1.42	0.91	0.76	0.39	1.30	0.88	0.87
CV upper	-0.67	-0.16	-0.47	-181.06	-0.01	0.24	0.25	0.21	-0.25	0.10	0.26	0.30	0.36
CV lower	0.70	0.20	1.02	-11.79	0.53	2.20	1.94	1.22	1.20	0.52	1.76	1.14	1.10
ICC	0.99	1.00	0.98	0.97	0.98	0.97	0.93	0.95	0.94	0.98	0.97	0.92	0.97
ICC intra lower	0.96	0.99	0.95	0.90	0.92	0.89	0.79	0.85	0.81	0.92	0.90	0.77	0.89
ICC intra upper	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.99	0.98	0.99	0.99	0.98	0.99

Table 2.4. Within-session between sprint reliability of kinematics and spatiotemporal variables during early acceleration.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.01	0.14	0.02	0.00	1.73	2.57	4.32	4.46	0.02	0.75	2.30	2.97	2.94
TE lower	0.01	0.10	0.02	0.00	1.24	1.84	3.10	3.20	0.01	0.54	1.65	2.13	2.11
TE upper	0.01	0.22	0.04	0.01	2.86	4.24	7.13	7.37	0.03	1.24	3.79	4.90	4.85
MDC %	12.39	8.56	5.63	-29.23	5.18	14.95	11.35	7.91	5.58	4.39	13.56	4.85	9.68
CV %	3.53	2.30	1.46	-54.80	1.52	4.02	3.24	2.27	1.66	1.40	3.90	1.33	2.62
CV lower	0.78	0.45	0.05	-153.48	0.09	0.62	0.96	0.46	0.56	0.61	1.11	0.23	0.66
CV upper	4.74	3.12	2.08	-11.55	2.15	5.52	4.24	3.06	2.14	1.75	5.12	1.81	3.48
ICC	0.47	0.41	0.89	0.99	0.73	0.64	0.75	0.51	0.87	0.76	0.60	0.62	0.74
ICC intra lower	-0.08	-0.15	0.68	0.98	0.32	0.16	0.35	-0.03	0.64	0.38	0.10	0.13	0.34
ICC intra upper	0.80	0.77	0.97	1.00	0.91	0.87	0.91	0.82	0.96	0.92	0.86	0.87	0.91

Table 2.5. Between-session reliability of kinematics and spatiotemporal variables during early acceleration.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.01	0.09	0.02	0.00	0.79	2.39	3.85	3.29	0.01	0.47	1.79	2.28	2.15
TE lower	0.00	0.07	0.01	0.00	0.57	1.71	2.76	2.36	0.01	0.33	1.29	1.63	1.54
TE upper	0.01	0.15	0.03	0.01	1.30	3.94	6.35	5.43	0.02	0.77	2.96	3.76	3.56
MDC %	9.32	5.71	4.89	-55.67	2.36	14.21	10.15	5.85	4.76	2.75	10.81	3.73	7.11
CV %	2.38	2.11	1.20	-63.68	0.60	3.67	2.87	1.35	1.28	0.75	2.85	1.10	1.87
CV lower	-0.17	1.01	-0.17	-172.33	-0.13	0.37	0.49	-0.28	0.04	0.13	0.34	0.36	0.27
CV upper	3.71	2.68	1.91	-6.77	0.95	5.40	4.12	2.20	1.92	1.08	4.17	1.49	2.71
ICC	0.74	0.88	0.94	0.97	0.95	0.81	0.87	0.78	0.91	0.92	0.83	0.88	0.82
ICC intra lower	0.35	0.65	0.82	0.91	0.84	0.50	0.62	0.43	0.73	0.75	0.54	0.66	0.52
ICC intra upper	0.91	0.96	0.98	0.99	0.98	0.94	0.96	0.93	0.97	0.97	0.95	0.96	0.97

Table 2.6. Within-sprint reliability of kinematics and spatiotemporal variables during upright sprinting.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.00	0.06	0.01	0.01	0.57	0.50	1.26	2.94	0.01	0.53	0.94	1.18	1.92
TE lower	0.00	0.04	0.01	0.01	0.38	0.33	0.83	1.94	0.01	0.35	0.62	0.78	1.27
TE upper	0.00	0.12	0.02	0.03	1.16	1.01	2.57	5.98	0.02	1.08	1.90	2.41	3.90
MDC %	5.12	3.61	1.76	-11.62	1.43	1.82	2.60	4.76	4.84	2.59	3.42	1.64	5.02
CV %	1.58	0.83	0.49	-2.25	0.46	0.52	0.55	1.17	1.43	0.73	0.88	0.37	0.93
CV lower	0.17	-0.21	0.00	-3.88	0.22	0.15	-0.12	-0.33	0.56	0.22	0.04	-0.10	-0.61
CV upper	2.20	1.29	0.70	-1.53	0.57	0.69	0.84	1.83	1.81	0.96	1.25	0.58	1.60
ICC	0.92	0.95	0.99	0.93	0.96	0.98	0.99	0.98	0.90	0.96	0.88	0.98	0.83
ICC intra lower	0.67	0.77	0.97	0.68	0.81	0.91	0.93	0.89	0.58	0.83	0.51	0.88	0.38
ICC intra upper	0.98	0.99	1.00	0.98	0.99	1.00	1.00	1.00	0.98	0.99	0.97	1.00	0.96

Table 2.7. Within-session between sprint reliability of kinematics and spatiotemporal variables during upright sprinting.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.01	0.11	0.04	0.01	0.96	1.11	2.97	3.27	0.01	0.76	1.13	1.24	1.89
TE lower	0.00	0.07	0.03	0.01	0.65	0.75	2.00	2.21	0.01	0.52	0.76	0.84	1.28
TE upper	0.01	0.21	0.07	0.03	1.84	2.12	5.69	6.26	0.03	1.46	2.17	2.38	3.63
MDC %	12.60	6.68	5.87	-10.97	2.38	3.96	6.14	5.38	6.60	3.65	3.99	1.72	4.89
CV %	3.18	1.35	1.52	-2.85	0.60	1.09	1.42	1.64	1.81	0.92	1.11	0.51	0.98
CV lower	0.07	-0.42	-0.22	-5.27	0.03	0.28	-0.18	0.52	0.18	0.04	0.22	0.19	-0.50
CV upper	4.54	2.13	2.28	-1.79	0.85	1.45	2.12	2.13	2.52	1.30	1.49	0.65	1.63
ICC	0.34	0.92	0.92	0.91	0.89	0.98	0.85	0.96	0.85	0.90	0.92	0.94	0.94
ICC intra lower	-0.37	0.70	0.69	0.64	0.60	0.90	0.47	0.84	0.48	0.63	0.68	0.75	0.75
ICC intra upper	0.80	0.98	0.98	0.98	0.97	0.99	0.96	0.99	0.97	0.98	0.98	0.99	0.99

Table 2.8. Between-session reliability of kinematics and spatiotemporal variables during upright sprinting.

				Touchdown					Toe-off				
	Contact time	Step Hz	Step length	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle	CM distance	CM angle	Trunk angle	Hip angle	Contralateral hip angle
TE	0.00	0.11	0.03	0.02	1.06	0.86	1.95	2.22	0.02	0.80	0.77	1.28	1.41
TE lower	0.00	0.07	0.02	0.01	0.72	0.58	1.32	1.50	0.01	0.54	0.52	0.87	0.95
TE upper	0.01	0.21	0.06	0.03	2.03	1.66	3.73	4.26	0.03	1.53	1.48	2.46	2.71
MDC %	10.89	6.60	4.53	-12.06	2.64	3.15	4.03	3.60	8.27	3.87	2.79	1.77	3.67
CV %	2.49	1.54	0.97	-3.00	0.64	0.75	0.83	1.12	2.27	1.05	0.78	0.45	0.76
CV lower	-0.85	-0.32	-0.74	-6.10	-0.03	-0.05	-0.47	0.40	-0.01	0.11	0.07	0.03	-0.40
CV upper	4.24	2.51	1.87	-1.38	1.00	1.16	1.52	1.50	3.47	1.54	1.15	0.67	1.37
ICC	0.50	0.89	0.96	0.84	0.89	0.97	0.94	0.99	0.84	0.91	0.96	0.95	0.94
ICC intra lower	-0.20	0.59	0.84	0.44	0.58	0.87	0.76	0.94	0.45	0.65	0.84	0.79	0.77
ICC intra upper	0.86	0.97	0.99	0.96	0.97	0.99	0.99	1.00	0.96	0.98	0.99	0.99	0.99

Table 2.9. Within-session reliability of sprint FV-profile variables.

	Vmax theoretical V0 (m/s)	Fmax theoretical F0 (N/kg)	Max ratio of forces (%)	Mean ratio of forces on 10 m (%)	Max Horizontal Power Pmax (W/kg)	Time @ 5 m (s)	Time @ 10 m (s)	Time @ 20 m (s)	Time @ 30 m (s)	Top speed (m/s)	FV-slope with N/kg instead of N
TE	0.09	0.27	0.51	1.48	0.51	0.02	0.02	0.03	0.03	0.06	0.04
TE lower	0.06	0.20	0.36	1.06	0.36	0.01	0.02	0.02	0.02	0.04	0.03
TE upper	0.15	0.45	0.84	2.44	0.84	0.03	0.04	0.05	0.05	0.10	0.06
MDC	0.25	0.76	1.41	4.10	1.40	0.05	0.07	0.08	0.08	0.17	0.10
MDC %	2.72	10.19			8.32	3.86	3.22	2.33	1.68	1.94	-12.40
CV %	0.75	3.12	1.12	1.72	2.55	1.13	1.01	0.70	0.51	0.51	-3.80
CV lower	0.19	1.41	0.16	0.57	1.16	0.39	0.51	0.26	0.21	0.07	-5.90
CV upper	1.00	3.87	1.76	3.05	3.16	1.45	1.22	0.90	0.64	0.70	-2.88
ICC	0.97	0.83	0.94	0.80	0.94	0.86	0.90	0.95	0.97	0.98	0.66
ICC intra lower	0.89	0.54	0.82	0.46	0.82	0.61	0.70	0.86	0.92	0.93	0.21
ICC intra upper	0.99	0.95	0.98	0.93	0.98	0.96	0.97	0.99	0.99	0.99	0.88

Table 2.10. Between-session reliability of sprint FV-profile variables.

	Vmax theoretical V0 (m/s)	Fmax theoretical F0 (N/kg)	Max ratio of forces (%)	Mean ratio of forces on 10 m (%)	Max Horizontal Power Pmax (W/kg)	Time @ 5 m (s)	Time @ 10 m (s)	Time @ 20 m (s)	Time @ 30 m (s)	Top speed (m/s)	FV-slope with N/kg instead of N
TE	0.10	0.24	0.59	1.80	0.40	0.02	0.02	0.02	0.03	0.06	0.02
TE lower	0.07	0.16	0.38	1.16	0.26	0.01	0.01	0.01	0.02	0.04	0.01
TE upper	0.22	0.54	1.30	3.96	0.87	0.04	0.05	0.05	0.06	0.14	0.05
MDC	0.28	0.68	1.64	4.99	1.10	0.06	0.06	0.06	0.07	0.18	0.06
MDC %	3.13	9.53			6.97	4.00	2.78	1.71	1.50	2.10	-7.37
CV %	0.87	2.87	1.76	2.95	2.13	1.17	0.87	0.53	0.45	0.57	-3.64
CV lower	0.24	0.78	0.58	0.58	0.49	0.23	0.25	0.15	0.10	0.14	-6.34
CV upper	1.15	3.79	2.27	3.98	2.85	1.58	1.14	0.70	0.61	0.77	-2.46
ICC	0.92	0.60	0.75	0.23	0.87	0.62	0.80	0.94	0.92	0.97	0.49
ICC intra lower	0.63	-0.09	0.10	-0.57	0.41	-0.16	0.20	0.70	0.62	0.82	-0.33
ICC intra upper	0.99	0.86	0.95	0.81	0.98	0.92	0.96	0.99	0.99	0.99	0.89

8.3. APPENDIX 3 (THEME III)

Table 3.1. Screening test scores for first testing round 2020.

Categories	Variables	Mean (n = 94)	CI95%	
			Lower	Upper
Player information	Age (yrs)	24.3	23.3	25.3
	Body Mass (kg)	76.8	75.4	78.2
	Height (m)	1.81	1.79	1.82
	Previous injury, n (%)	25/94 (36.2 %)		
Lumbo-pelvic control	Walk test (°)	7.80	7.67	8.16
	Kick-back test (°)	150	143	157
Posterior chain strength	Knee flexor strength (N.kg-^{1})	4.24	4.12	4.37
	Knee flexor strength asymmetry (%)	6.75	5.51	7.98
	Hip extensor strength (N.kg-^{1})	4.72	4.55	4.90
	Hip extensor strength asymmetry (%)	7.49	6.05	8.93
Range of motion	ASLR (°)	84.2	82.0	86.4
	ASLR asymmetry (%)	5.34	4.32	6.37
	Jurdan test (°)	76.0	73.7	78.4
	Jurdan test asymmetry (%)	8.48	7.13	9.83
Sprint mechanical output	Maximal theoretical horizontal force (N.kg-^{1})	7.82	7.67	7.96

Table 3.2. Training percentile thresholds in individual teams.

	Range of motion				Lumbo-pelvic control		Sprint mechanical output	Posterior chain strength			
TEAM	Jurdan test (^{o} 33% percentile)	Jurdan test asymmetry (N of positives =>15%)	ASLR (^{o} 33% percentile)	ASLR asymmetry (N of positives =>15%)	Kick-back test (^{o} 33% percentile)	Walk-test (^{o} 33% percentile)	F*0* (N.kg-^{1} 66 % percentile)	Hip ext. force (N.kg-^{1} 66 % percentile)	Hip ext. asymmetry (N of positives =>15%)	Knee flexor force (N.kg-^{1} 66 % percentile)	Knee flexor asymmetry (N of positives =>15%)
1	70.4	3	78.6	1	138	9.09	8.03	5.22	2	4.60	1
2	75.2	2	84.8	0	142	9.26	8.30	5.18	5	4.72	1
3	72.6	6	75.5	1	143	8.53	8.28	4.27	6	4.30	1
4	68.6	0	83.1	0	159	8.35	7.91	5.34	1	4.53	1
5	75.1	4	75.2	3	140	7.70	7.82	5.32	3	4.52	3
One-way ANOVA (p-value)*	0.27	**0.03**	0.86	0.51	**0.001**	0.28	0.07	**0.02**	0.47	0.49	0.93

* = Between team significance testing for baseline data, all values were normally distributed.

Table 3.3. Questionnaire for physical coaches 2019.

How consistently are the following exercise categories executed within pre and in season:

1.Isolative knee dominant high-tension eccentrics (Nordics, razor curls, sliders etc):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

2. Were knee flexor asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

3. Which ones were done on a weekly or close to all weeks basis:

4. Multijoint posterior chain exercises (Deadlift variations, GHR, hip thrust):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

5. Were hip extensor asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

6. Which ones were done on a weekly or close to all weeks basis:

7.Range of motion exercises for hamstring and hip flexors:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

8. Were range of motion asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

9. Which ones were done on a weekly or close to all weeks basis:

10. Lumbo-pelvic control low load exercises:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

11. Which ones were done on a weekly or close to all weeks basis:

12. Sprint drills aimed to improve maximal velocity sprint mechanics (A-skips, B-skips mini-hurdles etc):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

13. Which ones were done on a weekly or close to all weeks basis:

14. Maximal speed sprinting (above 90%), non-sport-specific:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

15. Which ones were done on a weekly or close to all weeks basis:

16. Early acceleration work, non sport-specific (5-10 m):

17. Which ones were done on a weekly or close to all weeks basis:

Table 3.4. Questionnaire for physical coaches 2020.

To find out what changed with implementing the intervention protocol:

1. From a group perspective, what is the increase in programming detail within the following categories:

Large increase (3), moderate increase (2), small increase (1), no change (0), small reduction (-1), moderate reduction (-2), large reduction (-3)

ROM perspective: -3 -2 -1 0 1 2 3

Pelvic control perspective: -3 -2 -1 0 1 2 3

Strength training: -3 -2 -1 0 1 2 3

Sprint training perspective: -3 -2 -1 0 1 2 3

2. From an individualized perspective, what is the increase in programming detail within the following categories:

ROM perspective: -3 -2 -1 0 1 2 3

Pelvic control perspective: -3 -2 -1 0 1 2 3

Strength: -3 -2 -1 0 1 2 3

Sprint training perspective: -3 -2 -1 0 1 2 3

3. To what extent do you consider the change in injuries was due to improvements in training compliance compared to last season?

Large contribution (3), moderate contribution (2), small contribution (1), no effect (0)

0 1 2 3

How consistently were the following exercise categories executed within pre and in season:

1.Isolative knee dominant high-tension eccentrics (Nordics, razor curls, sliders etc):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

2. Were knee flexor asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

3. Which ones were done on a weekly or close to all weeks basis:

4. Multijoint posterior chain exercises (Deadlift variations, GHR, hip thrust):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

5. Were hip extensor asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

6. Which ones were done on a weekly or close to all weeks basis:

7.Range of motion exercises for hamstring and hip flexors:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

8. Were range of motion asymmetries managed?
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0).

9. Which ones were done on a weekly or close to all weeks basis:

10. Lumbo-pelvic control low load exercises:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

11. Which ones were done on a weekly or close to all weeks basis:

12. Sprint drills aimed to improve maximal velocity sprint mechanics (A-skips, B-skips mini-hurdles etc):
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

13. Which ones were done on a weekly or close to all weeks basis:

14. Maximal speed sprinting (above 90%), non-sport-specific:
All weeks(3), at least every second week(2), at least once a month(1), less than once a month(0)

15. Which ones were done on a weekly or close to all weeks basis:

16. Early acceleration work, non sport-specific (5-10 m):

17. Which ones were done on a weekly or close to all weeks basis: